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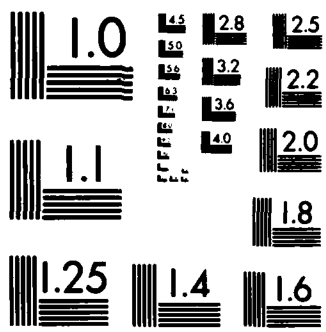

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COMPARISON OF THE ELECTROMAGNETIC PROPERTIES OF LIGHTNING AND EMP–

Results of Recent Lightning Studies

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Technical Report

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This report presents the results of the first phase of a program conducted by SRI International in an effort to address and resolve issues concerning the comparative interactions of lightning and EMP with aircraft. The program concentrated on using recently generated analytical and experimental data and interacting with lightning workers in an effort to define the current state of knowledge regarding the electromagnetic properties of lightning. This program was motivated by suggestions that there might be sufficient similarity between the effects of lightning and EMP that consideration of the electromagnetic effects of one would also suffice for the other.

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I INTRODUCTION

This report presents the results of the first phase of a program conducted by SRI International in an effort to address and resolve issues concerning the comparative interactions of lightning and electromagnetic pulse (EMP) with aircraft. The program concentrated on using recently generated analytical and experimental data and interacting with lightning workers in an effort to define the current state of knowledge regarding the electromagnetic properties of lightning. This program was motivated by suggestions that there might be sufficient similarity between the effects of lightning and EMP that consideration of the electromagnetic effects of one would also suffice for the other.

A. BACKGROUND.

Lightning and EMP are both energetic processes. Both radiate high-level transient electromagnetic fields that interact with aircraft to generate high currents in the skin and excite currents and voltages in interior systems. However, the source processes of lightning and EMP are vastly different, and the resulting electromagnetic fields have different temporal and spatial characteristics. These differences are important in determining the response of the aircraft in the transient environments.

The nuclear EMP environment consists of a high-amplitude transient pulse with a duration of hundreds of nanoseconds that covers a large geographical area as a propagating plane wave. This electromagnetic wave interacts with metallic bodies, including aircraft, within the covered area, inducing a large transient current pulse in the body. In general, the details of the EMP generated by a particular detonation depend on a number of parameters, including source location and weapon properties. In common with the procedures followed in other testing disciplines, envelopes defining the limits of expected EMP properties have been evolved by various agencies for use in EMP testing of their systems. A widely applied criterion pulse was evolved by the Air Force in connection with early EMP hardening programs.

A lightning flash typically lasts approximately 0.5 s and consists of a variety of discharges (frequently 10^4 or more) occurring at a number of locations scattered throughout virtually the entire active volume of the thunderstorm cell. The dimensions of the regions involved in these individual discharges range from meters to kilometers in length. Each event that generates a pulse in the overall lightning signal is associated with a discharge channel in or near the cloud. The dimensions of the channel and the processes occurring in it determine the electrical and spatial properties of the radiated signal.

In particular, although the magnitudes of the fields radiated by severe lightning may be comparable to EMP criterion levels very near the stroke channel, the lightning channel is a line source, so that the field intensity decreases rapidly with increasing distance from the channel. On the other hand, EMP field intensity remains constant over the dimensions of most practical systems. Thus, the way in which a system is excited by nearby lightning is not the same as the excitation produced by EMP.

Historically, the aircraft lightning community has been most concerned with the physical damage (e.g., burning and pitting of metal surfaces, structural damage to radomes) produced by the long-duration processes associated with lightning. In the 1970s, however, the various lightning communities began to place more emphasis on the high-frequency processes associated with lightning. This shift occurred as the result of several developments. First, better instrumentation became available to the atmospheric electrician, permitting the recording of high-frequency processes. Second, various needs for better information about high-frequency processes were perceived. The nuclear detection community needed to verify that its electromagnetic sensors would not be spoofed by lightning. About this time, the aviation community began to introduce digital avionic systems that were sensitive to the pulses generated by the high-frequency processes associated with lightning.

When modern sensors and recording equipment were applied to the study of lightning waveforms, it was found that the leading edge of the return stroke included processes with characteristic times of 100 ns in contrast to the 1 and 2 μs rise times generally accepted by the aircraft lightning community. The realization that lightning included high-frequency processes similar to EMP raised certain important technical questions concerning the relative interactions of these two electromagnetic sources with aircraft:

- What are the electromagnetic characteristics of lightning in comparison to those of EMP?
- Can the aircraft's normal exposure to lightning be used to make inferences regarding its EMP hardness?
- Do lightning tests during the development and certification of an aircraft provide insight regarding its EMP hardness?
- Can test procedures be evolved that address both lightning immunity and EMP hardness?

B. SCOPE AND OBJECTIVES.

The present work constitutes the first phase in a program to address and resolve the questions listed above by defining the current state of knowledge regarding the electromagnetic properties of lightning. This was achieved primarily by using published literature and interacting with workers in the field of atmospheric electricity. In the future, it might be appropriate to become more involved in the analysis and planning of experiments, or even to participate in conducting experiments, to obtain essential data that might not otherwise be generated. In particular, it might be necessary to become involved in flight-test experiments to define the nature of the electromagnetic environment at aircraft altitudes in the immediate vicinity of a thunderstorm cell, particularly in the frequency range above 3 MHz, where aircraft electromagnetic responses occur.

The objective of the program was to interact with workers in the area of lightning characterization to determine the present state of knowledge regarding the electromagnetic characteristics of lightning, particularly in the frequency range above 3 MHz. A further objective was to become familiar with plans for future work to determine the degree to which it might address the issues of interest here.

As part of the program, a subcontract was issued to Lightning Location and Protection, Inc., of Tucson, Arizona, to permit Drs. M. A. Uman and E. D. Krider to refine certain of their relevant lightning studies. The results of this activity are presented in Appendix A of this report.

II LIGHTNING — A HISTORICAL PERSPECTIVE

A. LIGHTNING PROCESSES.

1. The Thunderstorm Cell.

The classification of a storm as a thundercloud or thunderstorm requires that thunder be heard, which in turn implies the presence of lightning.[1*] These storms are composed of strongly convective cumulonimbus clouds generally accompanied by strong wind gusts and rain, or sometimes hail or snow. Thunderclouds usually develop as the warm, moist air near the earth rises and replaces the denser air aloft. As a consequence of this overturn, the condensation of atmospheric water vapor occurs forming a visible cloud of water droplets. The heat associated with the phase changes of water speeds the overturn: release of the heat of vaporization by condensing water vapor enhances the updrafts, while cooling, caused by evaporation of condensed water, can help drive the downdrafts which replace some of the ascending subcloud air.

Cloud physicists do not agree on the mechanisms responsible for thunderstorm electrification. It has generally been assumed that negative charge is selectively separated and transported downward by falling precipitation particles. Mechanisms proposed for producing the charge separation include induction charging resulting from particle collisions in an existing electric field, to charge separation occurring as the result of ice crystal splintering.[1] The study of particle electrification is an active area of cloud physics.

The physical dimensions of a mature thunderstorm cell are shown in Figure 1.[2] In general, the cell is 5 to 10 km in diameter and extends to a height of 12 to 15 km or more. Frequently, a mature cell also incorporates an "anvil" structure at its top caused by the blow-off of cloud particles by the horizontal winds at the altitude of the thunderstorm top.

Also shown in Figure 1 is an early electrostatic model for the distribution of charge in a South African thundercloud suggested by D. J. Malan.[3] It was constructed using ground measurements of electric field intensity in the vicinity of thunderclouds. Although electrostatic charge models are appealing for a variety of reasons (they are simple in concept, easy to use, and permit a particularly simple linkage of external field observations to

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*References are listed at the end of this report.

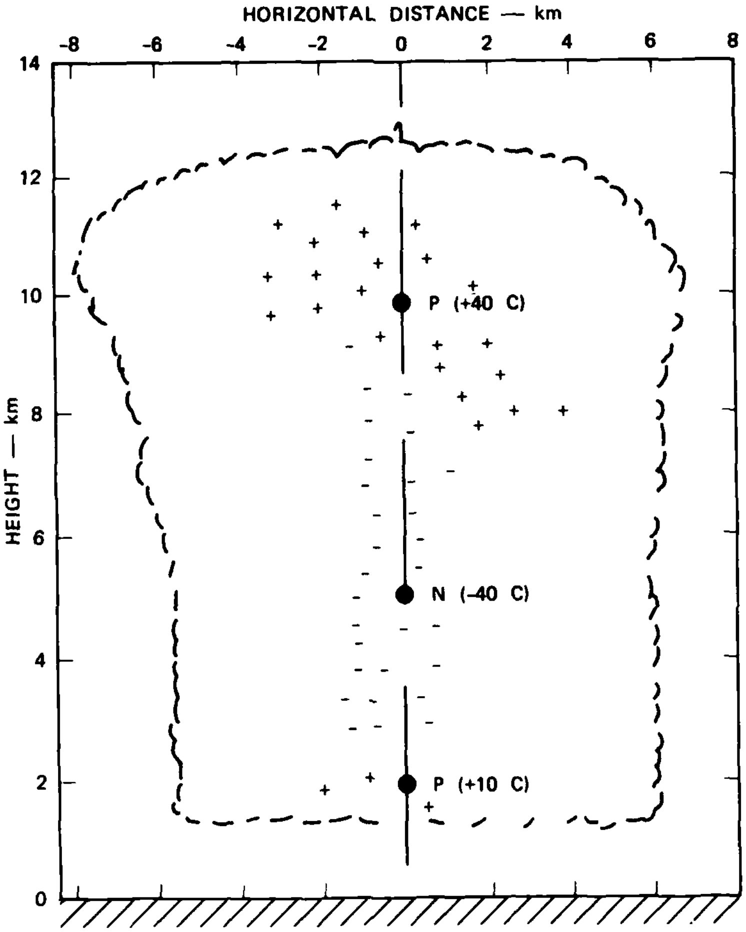

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FIGURE 1 IDEALIZED CROSS SECTION THROUGH A MATURE THUNDERSTORM CELL AND PROBABLE DISTRIBUTION OF THE THUNDERCLOUD CHARGES. Solid black circles indicate locations of effective point charges, typically, P = +40 coul at 10 km, N = -40 coul at 5 km and p = +10 coul at 2 km to give observed electric field.

internal charge magnitudes), researchers have pointed out that the use of such models for thunderstorm charge distributions gives erroneous results if (as is generally believed) the electrical conductivity of the cloud and the surrounding atmosphere are functions of position.[4-6] Accordingly, substantial work is currently under way to develop more accurate models of the charge distribution within thunderstorm clouds.

2. The Lightning Flash.

A complete lightning discharge is called a flash and consists of a large number of diverse transient processes that generate high-level electromagnetic signals in the vicinity of the flash over a typical period of 0.5 s. These processes include a large number of transient probing processes that occur within the cloud, followed by the stepwise propagation of the many leaders, at least one of which reaches the ground and by a dramatic return stroke carries currents of tens or hundreds of kiloamperes along the cloud to ground channel. Once the conducting channel to the cloud is established, additional leader and return strokes generally occur (leading to the flickering appearance of lightning).

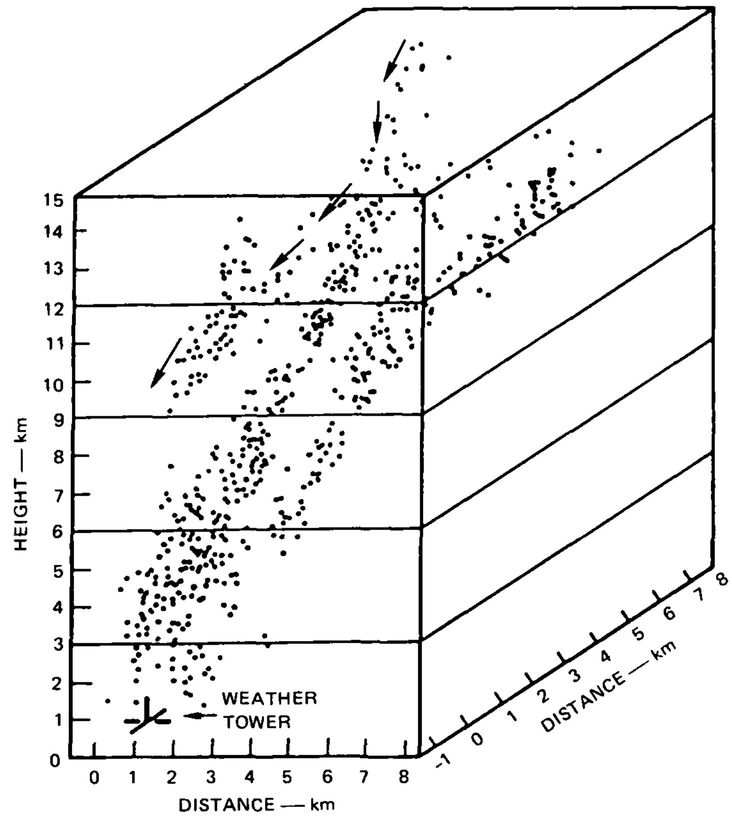
Some lightning flashes do not carry charge to ground. They merely redistribute charge between the charge centers within the cloud and are known as intracloud lightning. In general, the peak current levels in intracloud lightning are an order of magnitude lower than in cloud-to-ground strokes.

The degree to which discrete electrical discharges are distributed throughout the thunderstorm cell during a lightning flash is illustrated in Figure 2.* Individual discharges are spread throughout much of the 8 by 15 km region illustrated in the figure. Rustan, Uman et al.[9] located 48,000 VHF sources during the 1 s period of the flash illustrated (three ground strokes followed by an intracloud stroke).

Figure 3 is a schematic illustration of the major processes typically involved in a single cloud-to-ground lightning flash. A complete lightning discharge (duration ≈ 0.5 s) is composed of several component discharges (luminous for ≈ 100 μs) called strokes, which are separated by about 40 ms. Each stroke consists of a weakly luminous leader, which propagates to the ground, followed by a very luminous return stroke, which propagates from the ground to cloud.

---

*On 19 July 1976, the 150 m weather tower at Kennedy Space Center (KSC) in Florida was struck by a three-stroke lightning flash. At this time, the Thunderstorm Research International Program 1976 (TRIP-76),[7] hosted by the National Aeronautics and Space Administration (NASA) at KSC was under way, and a number of participating experimenters recorded various features of the flash. Uman and Rustan[8,9] have analyzed and reported on many of the electromagnetic properties of the flash.



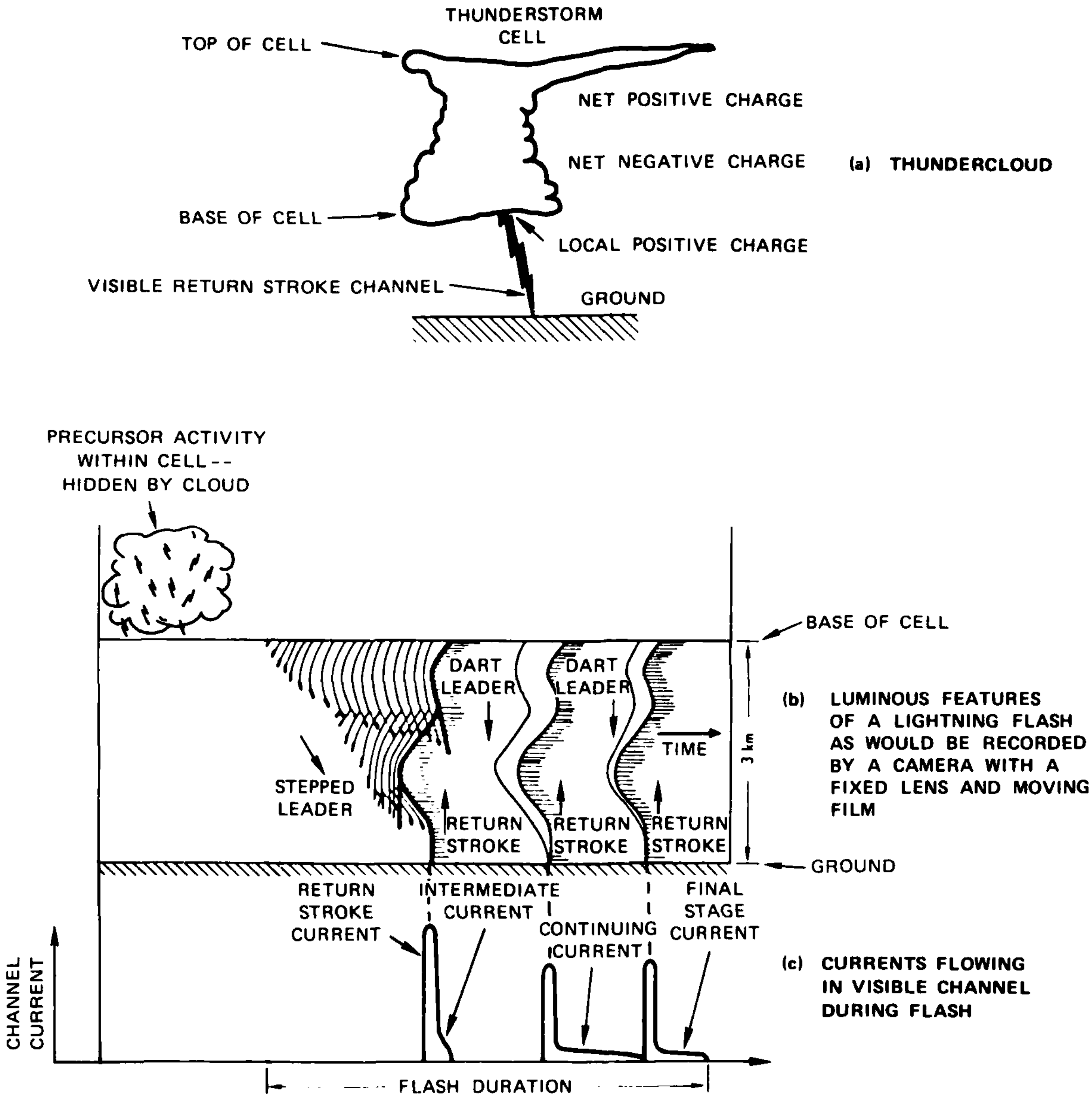
NOTE: Arrows indicate direction of propagation of groups of sources which occured in bursts

SOURCE: Reference 9

FIGURE 2 VHF NOISE SOURCE LOCATIONS DURING THE THREE-STROKE LIGHTNING FLASH TO THE 150-m WEATHER TOWER AT KSC ON 19 JULY 1976 AT 16:59:59

The first cloud-to-ground predischarge in a flash is called the stepped leader. (Actually, as indicated in Figure 3, several leaders or branches proceed toward the ground simultaneously.) The stepped leader appears to move downward in luminous steps of roughly 50 m in length with a pause between steps of about 50 μs. During the pause, the stepped-leader channel is not luminous enough to be recorded on photographic film using standard streak-camera techniques. Each leader step becomes bright and observable in less than a microsecond. In Figure 3b, the 50 m steps appear as darkened tips on the faintly luminous channel extending upward into the cloud. Typically, the average velocity of the stepped leader during its trip to the ground is 1.5×10^5 m/s. Peak currents in a leader step are of the order of 10^3 A.

When the stepped leader has lowered a charged column of high negative potential to near the ground, the resulting high electric field at the ground is sufficient to cause upward-moving discharges to be initiated from the ground or from objects on the ground



SOURCE: Reference 3

FIGURE 3 SCHEMATIC ILLUSTRATION OF PROCESSES AND CURRENTS OCCURING DURING A FLASH TO GROUND toward the leader tip. When one of these discharges contacts the leader, the bottom of the leader is effectively connected to ground potential, while the remainder of the leader is at negative potential and is negatively charged.* The situation is somewhat similar to a transmission line charged to a constant potential with a short circuit applied at its end. The leader channel acts like a transmission line (nonlinear) supporting a very luminous return stroke. The return stroke wavefront, an ionizing wavefront of high electric-field intensity, carries ground potential up the path produced previously by the stepped leader. The return stroke wavefront propagates at a velocity of typically one-third to one-tenth the speed of light, making the trip between cloud base and ground in a time of the order of 70 μs. The region between the return stroke wavefront and ground is traversed by large currents. The net negative charge deposited on the leader channel is effectively lowered to earth through the highly conducting channel beneath the return stroke wavefront.

Once the stroke current has ceased to flow, the lightning flash may end. However, if additional charge is made available to the top of the channel, the flash may contain additional strokes (a multiple-stroke flash). If additional charge is made available to the decaying return-stroke channel in a time less than about 100 ms, a continuous or dart leader will traverse that return-stroke channel, carrying the cloud potential earthward once more. The dart leader thus establishes the conditions for the second return stroke. The dart leader appears to be a luminous section of channel about 50 m in length which travels smoothly earthward at about 2×10^6 m/s, an order of magnitude faster than the average velocity of the stepped leader.

Each process involved in the total flash radiates electromagnetic pulses of varying amplitude, risetime, and duration. The return stroke phase(s) of the flash are responsible for the most energetic of these pulses, with field spectra having a first breakpoint at about 10 kHz, followed by $1/f$ frequency dependence to a few megahertz with a $1/f^2$ (or possibly faster) roll-off at higher frequencies. Other processes in the cloud-to-ground flash, and many of the processes involved in intracloud flashes, radiate similar amounts of energy above 3 MHz, and very little energy below 3 MHz.

Most of the currently available information about lightning and its electromagnetic properties has been generated by ground measurements, either of stroke currents to instrumented towers or of electromagnetic signals received at ground locations. Until recently,

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*In addition there are many other stepped leaders and branches that do not reach the ground before this first leader completes its course and the return stroke begins. The return stroke discharges the region and the static field is quickly reduced so that the formation of the incomplete leaders is halted.

airborne characterization of lightning strikes consisted primarily of recording the physical damage observed on the aircraft so that simulators could be adjusted to produce the same damage to the material involved.

B. LIGHTNING STROKE PARAMETERS.

In connection with the study of the lightning threat to the Safe-guard system, Cianos and Pierce collected and consolidated available lightning data and presented the results in a form useful to an engineer concerned with damage caused by the effects of ground lightning on systems.[10] Their report presents statistics on many of the important discharge parameters. In addition, Pierce considered the implications of the available lightning stroke statistics on the problem of lightning simulation.[11] Relevant portions of his results are summarized here.

1. General.

Both intracloud and ground flashes are probably initiated within the cloud in restricted areas of very high electric field. Typically, these areas are concentrated around an altitude of about 3 km with the cloud base at 1 km. It follows that the probability of an aircraft intercepting a flash to ground is almost uniform from 0 to 3 km and then drops off sharply with increasing altitude. Intracloud discharges begin to be encountered at 1 km. They are experienced more frequently as altitude increases, and as the 3-km level is approached, the chances of meeting an intracloud flash or a discharge to ground are about equal. The maximum incidence of intracloud flashes is at about 6 km; few intracloud flashes reach to the cloud top (12 km).

Electrically, intracloud flashes and discharges to earth have one major difference. Cloud-to-ground flashes contain return strokes within which very high peak currents ($i \approx 100$ kA) and rates of current rise ($di/dt \approx 100$ kA/μs) are experienced. There are no true return strokes, with their associated large values of i and di/dt, in intracloud discharges.

The deleterious effects of lightning on aircraft are conveniently separated into four categories associated with distinct electrical causes. The effects are:

(1) Thermal vaporization and magnetic forces. Cause: return-stroke current of the order of tens of kiloamperes.

(2) Undesirable electromagnetic coupling from direct strokes. Cause: rates of current change, typically tens of kiloamperes per microsecond.

(3) Burning and erosion. Cause: intermediate currents of the order of kiloamperes for milliseconds. Also, continuing currents of the order of hundreds of amperes for hundreds of milliseconds.

(4) Upset and damage of sensitive circuits. Cause: electromagnetic coupling from flashes that are "near misses."

Both intracloud discharges and flashes to earth are thought to be almost equally potent with regard to Effect (3). For Effect (4), over most frequencies there is little difference between the two types of discharge. However, Effects (1) and (2) are produced chiefly by return strokes and therefore by flashes to earth. Tests geared to the severity of flashes to ground will therefore adequately cover intracloud discharges.

2. Statistics of Lightning Parameters.

Although many parameters are required to define all of the processes involved, many are of little importance as potential hazards. Some other parameters are of greater importance, and our knowledge of them must be constantly updated. Two important parameters for the return stroke in the flash to earth are the peak current, i_p, and the peak rate of current rise, di/dt. Another important return-stroke parameter is the half-value time required to decay from the peak i_p to $i = 0.5\ i_p$. The statistics of return-stroke parameters are represented in Figure 4 for the usual flash transporting negative charge to ground.[11] The representation is conveniently formulated in terms of the log-normal

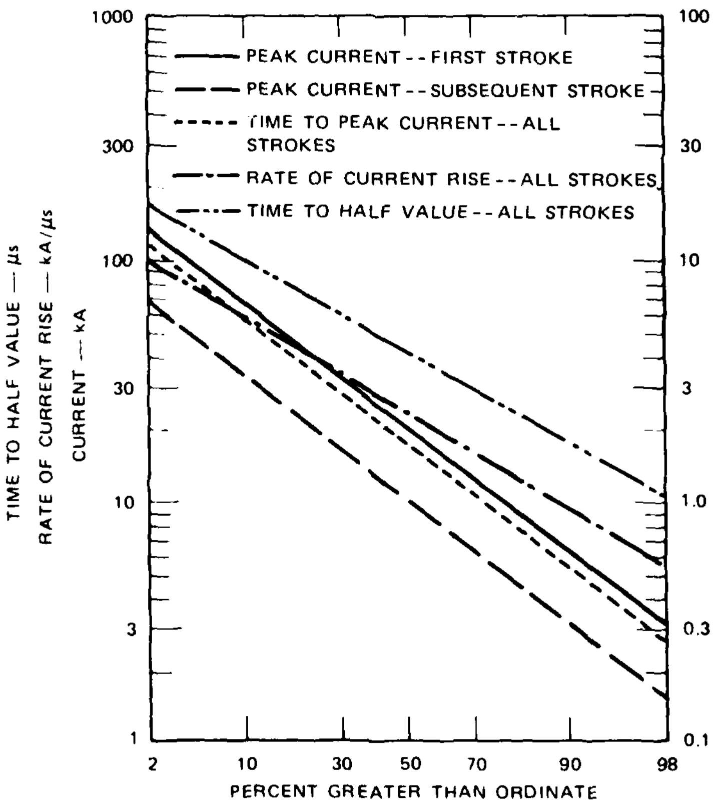

FIGURE 4 STATISTICS FOR RETURN-STROKE PARAMETERS--NEGATIVE STROKES

distribution; this distribution is closely obeyed by many parameters. Figure 4 terminates at the 2% point. The distribution is easily extrapolated to more extreme values, but the greater the extrapolation the greater the uncertainty.

The main surge of return-stroke current is usually followed by an "intermediate" current of a few kiloamperes lasting for a few milliseconds. Although intermediate currents have been measured, and characteristics of the currents have been deduced from observations of atmospherics, no statistical information on intermediate currents is readily available. This is unfortunate, since it is believed that intermediate currents are the type most likely to produce metallic puncture when -- as is common with aircraft -- the point of flash attachment is being swept along the fuselage by the windstream.

Most discharges include a phase of continuing current. Intracloud flashes consist predominantly of continuing current, with superimposed K-recoil surges. Even for the discharge to ground, continuing currents rather than return-stroke surges produce most of the charge transfer. Statistics for continuing currents are shown in Figure 5.

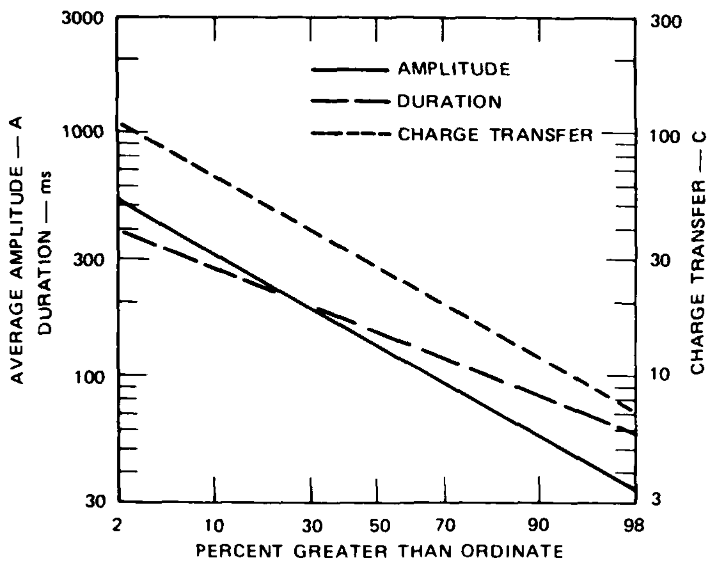

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FIGURE 5 STATISTICS FOR CONTINUING CURRENTS--NEGATIVE FLASHES TO GROUND (after Pierce)

C. LIGHTNING SPECTRAL DATA.

Historically, atmospheric electricians have had to use their ingenuity to devise schemes to permit them to apply available but severely limited instrumentation to the study of lightning parameters. For example, until very recently, no instruments were available that were capable of recording the high-frequency processes in the time waveform of the lightning current or its radiated signal. Even today, it is difficult to devise adequate high-speed data storage and record the entire waveform with sufficient speed to define important details. Accordingly, many experimenters were led to carry out measurements to study the high-frequency properties of lightning using setups of the sort illustrated in Figure 6. With this arrangement it is only necessary to have available receivers that are capable of covering the frequency range included in the lightning spectrum. Limitations of receiver bandwidth and recorder response restrict one's ability to distinguish single events, but it is possible to make inferences regarding the existence of high-frequency processes (fast rise times) and other important characteristics of the lightning flash.

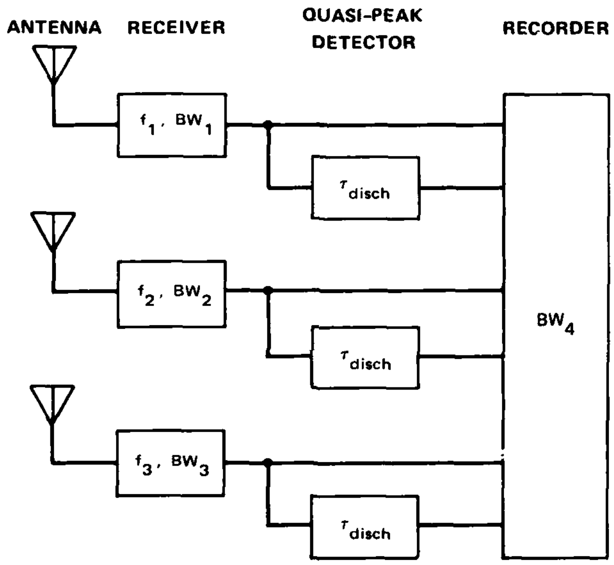

FIGURE 6 EXPERIMENTAL ARRANGEMENT USED FOR MEASURING LIGHTNING SPECTRAL PROPERTIES

A further practical consideration for early experimenters was that a need existed for data regarding lightning noise levels throughout the RF spectrum. Since narrowband communication receivers were the principal devices of concern, a narrowband measurement of noise spectral-density was adequate.

Thus, over the years, measurements of the sort illustrated in Figure 6 have been made by a number of experimenters using equipment with a variety of characteristics.[12-19] Varying degrees of attention were paid to locating the storm or the lightning events. In some cases, the center frequency of one or more of the receivers was switched during a storm to permit more frequencies to be covered. The receiver ouput bandwidth varied with the experimenter, and some used quasi-peak detectors with a discharge time constant as long as 0.6 s.[13]

At this time, it is appropriate to observe that narrowband measurements tend to yield a spectrum that is a composite of the processes in the lightning flash as follows. If the frequency spectrum of a single input pulse is essentially flat over the passband B of a narrowband receiver, the output signal will correspond to the receiver's impulse response. The impulse response of a tuned narrowband system is an exponentially decaying sinusoid (or its exponentially decaying envelope if an appropriate output envelope detector is included). The output decay time constant, τ, is given by $\tau \approx Q/\pi F_0$, where $Q = f_0/BW$. Therefore, $\tau \approx 1/\pi BW$. As an example, Horner's measurements[12,14] were made with receiver bandwidths of 250 Hz. Thus, the characteristic output decay time of his system is $1/250\pi \approx 1.3$ ms. For an average lightning interpulse spacing of 50 μs, this means that 28 additional pulses have arrived and contributed energy before the effect of the first one has died out. (More detailed analyses of these effects are presented in Appendix B.)

The "stacking" of pulses does not occur in wideband systems such as the wiring of an aircraft, so including the contributions from successive pulses in the spectral data injects major unnecessary complications into its application and interpretation for these purposes.

Oetzel[20] collected the available narrowband data, adjusted it as best he could to a common bandwidth of 1 kHz and a lightning distance of 10 km, and plotted the resulting individual spectra. Later, Cianos and Pierce[10] added the results of some additional measurements, but instead of presenting the data as a collection of spectral curves generated by a variety of experimenters, they simply plotted the data points as shown in Figure 7. To unify the presentation, they plotted on the same figure a 1/f line representing an empirical relationship between peak field strength and frequency derived earlier for the VLF range.[21]

It is evident from Figure 7 that at frequencies above about 1 MHz there is a great spread in the data and that the empirical 1/f line lies generally along the upper bound of the narrowband data, while a $1/f^2$ line beginning at 1 MHz would lie along the lower bound. (In retrospect, it is unfortunate that Cianos and Pierce, who clearly understood the complexities of lightning processes, chose to plot the single line on their collection of data. Although they admonished the reader that "the 1/f line ... is only an analytical tool and does not imply any physical justification," this single line is now used widely, without the admonishment, as representing the Cianos and Pierce's perception of the lightning spectrum.)

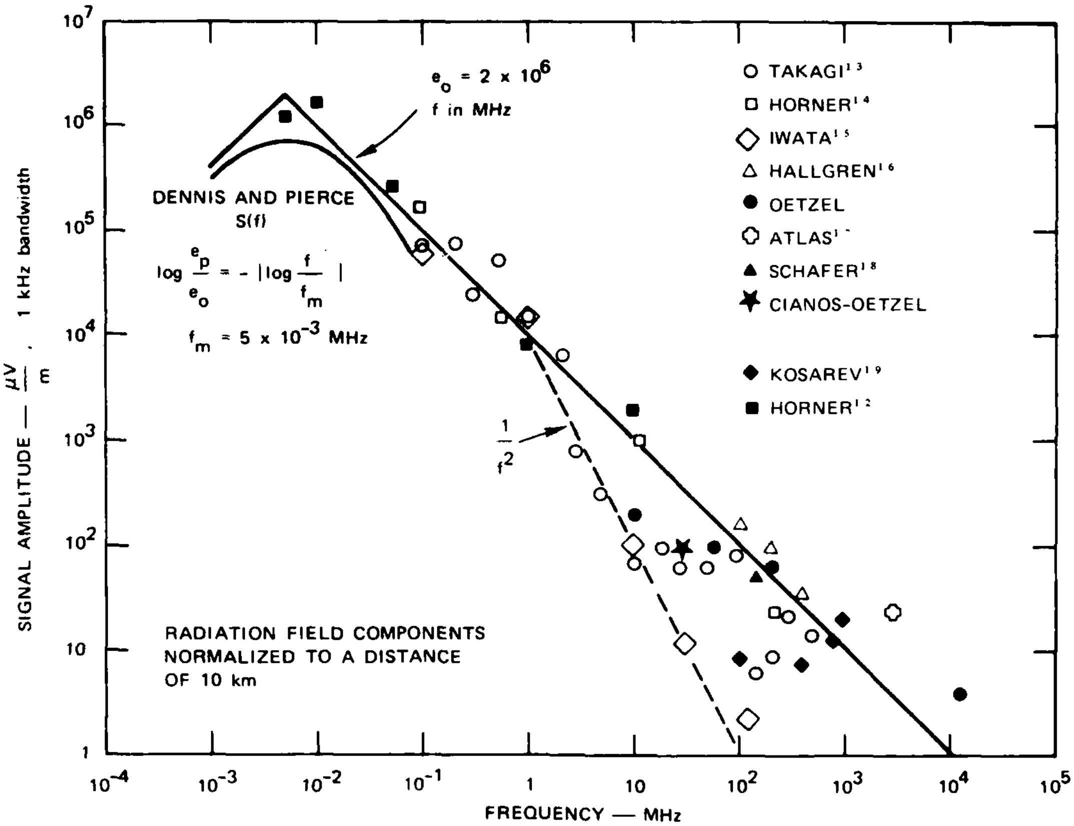

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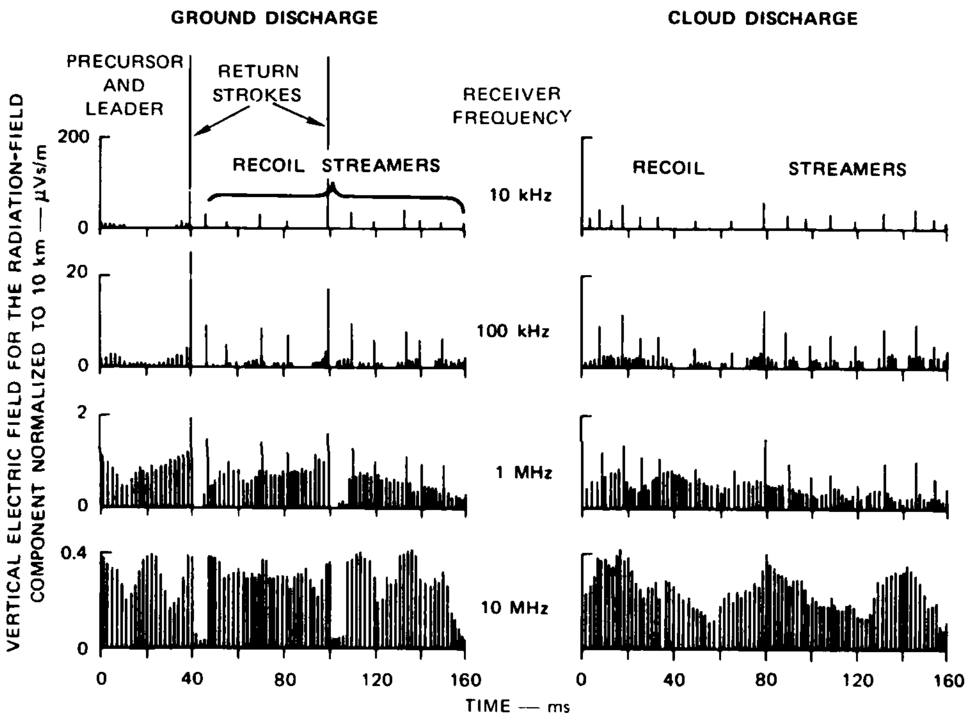
FIGURE 7 PEAK RECEIVED AMPLITUDE FOR SIGNALS RADIATED BY LIGHTNING

It is interesting to consider the data above 1 MHz in Figure 7 more carefully to determine if there is a reason for the great spread observed. Consider first Iwata's data, which lie along the dashed $1/f^2$ line.[15] Iwata's receivers had bandwidths of 10 kHz and 80 kHz (characteristic times of 32 μs and 4 μs), so that his system response was sufficiently fast that significant pulse "stacking" did not occur (even for τ = 32 μs, the worst-case error for an infinite number of pulses spaced 50 μs apart is +27%). As was indicated earlier, Horner's system[12] had a bandwidth of 250 Hz, so that considerable pulse stacking would be expected and could drive his data upward to as high as 16 times the single-pulse levels. Takagi's system[13] used a quasi-peak detector with a decay time of 0.6 s, so his measurements constitute a composite of the entire flash. The great variability in Takagi's data probably stems from the fact that he had available only two receivers, which were shifted from frequency to frequency as the storm progressed.

In conclusion, it appears that direct measurement of spectral density using multiple narrowband receivers can yield data valid for single-pulse analysis, provided the receiver bandwidth is sufficiently great to prevent stacking. This was done by Iwata, whose data in Figure 7 lie along the dashed $1/f^2$ line and are also in excellent agreement with the FFT data of Uman and Krider (discussed in Section III-B).

If the bandwidth of the system of Figure 6 is increased sufficiently, it becomes possible to distinguish many of the individual events in the lightning flash,[22] and the data assume the form shown in Figure 8 (reproduced from Ref. 10). At very low frequencies (VLF, 3 to 30 kHz), the pulses are discrete and are generated principally by the return stroke and/or recoil streamers (K-changes). As the frequency increases, the number of



SOURCE: Reference 10

FIGURE 8 STRUCTURE (illustrative) OF THE FIELDS RADIATED BY LIGHTNING AS A FUNCTION OF TIME AND FREQUENCY

pulses per flash also increases, with a maximum of about 10^4 per discharge for very high frequencies (VHF; between 30 to 300 MHz); the disturbance accompanying the flash is then quasi-continuous. These pulses appear to be associated with the initial leader, including its steps, and also with the electrical breakdown processes accompanying probing leaders moving within the cloud.

These probing leaders can occur, for a flash to earth, between return strokes or after the final stroke; for an intracloud discharge, their presence is possible at almost any stage of the discharge.* An interesting feature is that the signals at HF and VHF associated with return strokes and K-changes are not strong and are indeed partly "quenched" following the occurrence of return strokes and K-changes. It is believed that this quenching is due to a temporary absence of probing leaders.

Le Vine, in discussing approaches to explaining lightning spectra,[25] observes the following:

> "... the discrete nature (i.e., identifiable individual impulses) of the radiation persists at all frequencies in this example, suggesting that the flash consists of a sequence of individual broad-band discharges."
>
> "The transition from return stroke dominated radiation at low frequencies to a complex pattern of radiation from many events at higher frequencies, has important implications for understanding the spectra of radiation from lightning. At frequencies near the spectral peak return strokes are the dominant source of radiation, and consequently, measurements at these frequencies (VLF) are representative of the spectra of a particular individual event, the return stroke. At higher frequencies, many events contribute to the radiation, and measurements tend to be averages over periods long compared to the time between events. For example, the measurements of Horner and Bradley[14] are spectra of the composite flash obtained by averaging over a few hundred milliseconds. Hence, there are two spectra to be addressed in any theory, the spectrum of individual events and the spectrum of the composite flash..."

Thus, as will be discussed in more detail later, great care must be exercised in applying narrowband ground-measurement data to wideband airborne systems.

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*The existence of these pulses was used as the basis of a VHF lightning direction finding technique proposed by Oetzel and Pierce in 1969[23]. The system was built and demonstrated by Cianos, Oetzel, and Pierce in 1972[24]. This same concept was ultimately applied by NASA in building the Lightning Detection and Ranging (LDAR) system at Kennedy Space Center.

III RECENT LIGHTNING STUDIES

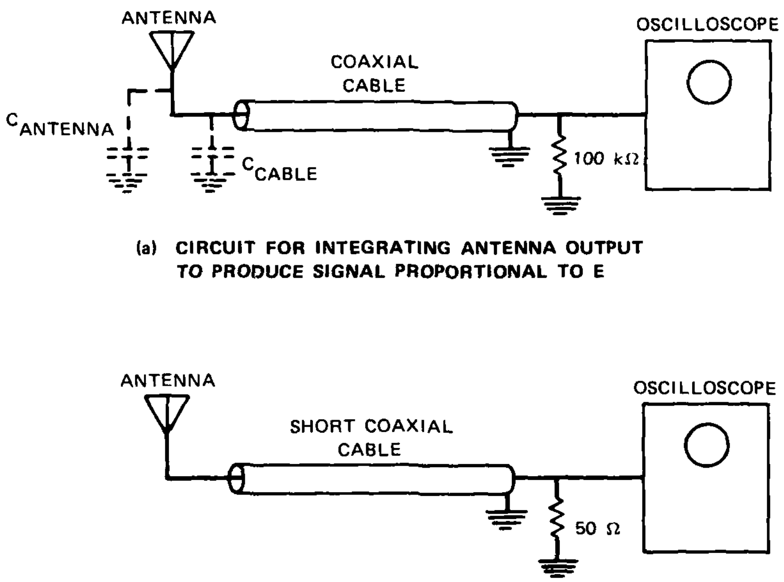
In recent years, there has been substantial activity in the general area of lightning characterization. The work has included ground-based measurements, airborne experiments, and analytical studies by a number of investigators. Coordinated efforts of large numbers of experimenters during the successive Thunderstorm Research International Programs (TRIP) have fostered the comparison of data obtained by a number of experimenters studying selected lightning events. Certain results of this recent work are of great interest for our purposes.

The experimental activity has included a number of ground-based measurements directed toward improving the definition of the leading edge of the lightning stroke. This work is possible because of the development of new types of sensors and high-speed transient recording instrumentation.

A. TIME WAVEFORM MEASUREMENTS.

Krider and his students have been conducting studies of the electromagnetic signals generated by lightning using the ground-based setup illustrated in Figure 9. Two electric dipole sensors and recording instruments are used. In Figure 9a, the circuit resistance is deliberately kept high so that the antenna output is integrated by the capacitance of the antenna, cable, and oscilloscope input to generate an output signal to the oscilloscope directly proportional to antenna open-circuit voltage or to the electric field E. In Figure 9b, a short length of coaxial cable terminated in a low resistance (50 Ω) is used so that the antenna short-circuit current, or dE/dt, is measured. Their early instrumentation had limited bandwidth capabilities,[26] and they found that the shortest pulse rise times in their measured data corresponded to the rise time limits of their instruments. With the greater availability of high-speed instrumentation and increased awareness of the importance of the fast processes associated with lightning, the instrumentation system was updated to a bandwidth of 35 MHz and was used to study rise times of lightning return stroke fields.[27] Some results of this work are reproduced in Figures 10 and 11.

The mean rise time of 90 ns shown in Figure 10 is much lower than the value of 1.5 to 2 μs for mean time-to-peak shown in Figure 4 and used in conventional lightning models.[10] Some of the difference comes about from the fact that time-to-peak is defined as the total rise time between the first detectable onset of the current surge and the time of peak current, whereas the rise times shown in Figure 10 are taken between the 10% and 90%



(a) CIRCUIT FOR INTEGRATING ANTENNA OUTPUT TO PRODUCE SIGNAL PROPORTIONAL TO E

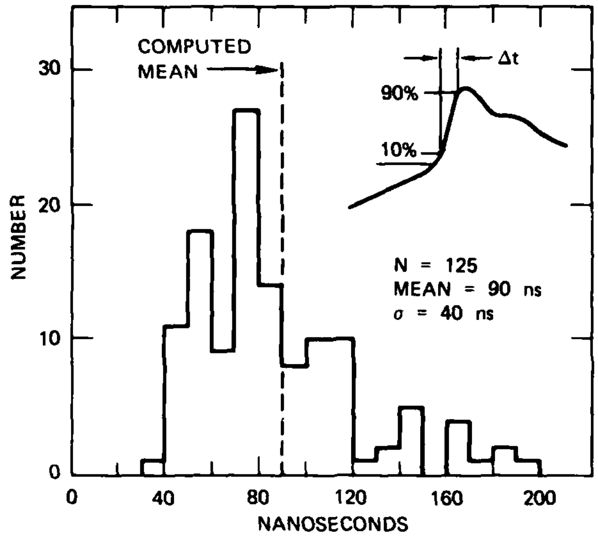
(b) CIRCUIT TO PRODUCE SIGNAL PROPORTIONAL TO dE/dt

FIGURE 9 SENSORS AND CIRCUITS USED BY KRIDER AND COWORKERS TO PRODUCE OUTPUTS PROPORTIONAL TO E AND dE/dt

points on the fast-rising portion of the pulse leading edge. The remainder of the difference probably stems from the better definition of the lightning waveform afforded by the use of modern, wideband instrumentation.

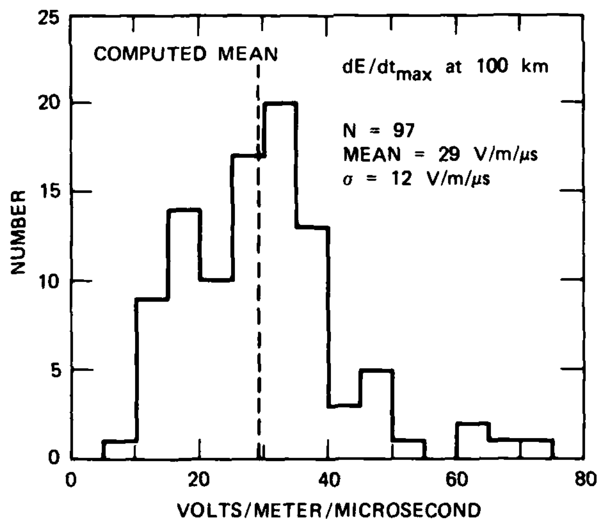
The dE/dt data of Figure 11 have been used by Weidman and Krider to infer rates-of-change of return stroke channel current.[27] Their analysis indicates that a mean dE/dt at 100 km of 30 Vm^{-1} μs^{-1} (as shown in Figure 11) implies that the maximum rate of change of stroke channel current, dI/dt, is in the range 50 to 75 kA/μs. These values range from two to three times the mean dI/dt for first return strokes shown in Figure 4.

Krider and his co-workers have been aware of the need to take precautions to preserve the high-frequency components in the radiated electromagnetic pulse. Accordingly, they set their instrumentation van up at the edge of an ocean or bay and used only data generated by lightning strikes to points on the ocean with no intervening land. Each flash was located using a commercial lightning location system manufactured by Lightning Location and Protection, Inc. Thus, all of their measurements were made on over-water propagation paths to minimize attenuation of high frequencies due to ground losses.



SOURCE: Reference 27

FIGURE 10 HISTOGRAM OF THE 10-90% RISE TIMES OF THE FAST-FIELD TRANSITIONS PRODUCED BY RETURN STROKES



SOURCE: Reference 27

FIGURE 11 HISTOGRAM OF THE MAXIMUM RETURN-STROKE dE/dt VALUES NORMALIZED TO A DISTANCE OF 100 km

Unfortunately, this procedure also means that all of the flashes studied are cloud-to-saltwater events. There is speculation that the high electrical conductivity of the salt water can permit the rise time of the return stroke to be higher than when the lightning terminates on poorly conducting soil. (In general, reported measurements of direct-strike currents to towers on the ground have not displayed the submicrosecond rise times inferred from the radiated field measurements. Recent — but as yet unreported — tower measurements apparently yield shorter rise times, so the reported slow rise times may have been due to instrument limitations). To test the degree to which ground propagation loss affects the rise times of cloud-to-saltwater signals, Weidman and Krider determined the mean fast-transition risetime for 29 return strokes that struck seawater at a distance of 10 to 35 km, but that propagated over about 3 km of land.[27] They found it to be 201 ns, which is roughly twice the mean value of 90 ns shown in Figure 10 for a strike to seawater and propagation over saltwater along the entire path. They argue that the fact that propagation does limit the field rise times that can be measured over land explains why the submicrosecond components of leaders and return strokes were not accurately measured earlier.

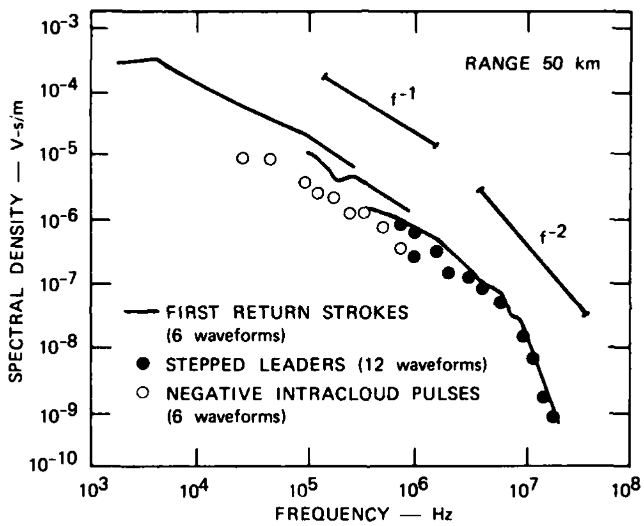
As part of their subcontract activity on the present program, Uman and Krider investigated the relationship between return-stroke rise time, dE/dt, and total field change, ΔE. Their results (presented in Appendix A) indicate that the two parameters do appear to be linearly related, implying that a large peak current will produce a large dI/dt. There is a great deal of spread in their data, however, and several questions remain to be resolved for the high values of dE/dt.

Baum has been concerned with the spoofing of nuclear-event detection systems by the high-frequency components of lightning.[28] He and his contractors have made measurements, with 10 ns resolution, of the electromagnetic signals radiated from nearby lightning strokes on South Baldy Peak near Socorro, New Mexico. They observed characteristic times for the electromagnetic fields (peak field divided by peak derivative) ranging from 100 ns to 30 ns. These results are in good agreement with those of Weidman and Krider, as shown in Figure 10.

B. LIGHTNING SPECTRAL STUDIES.

To study the spectral properties of the various individual lightning processes, Weidman et al. first made oscilloscope recordings of the E-field waveforms radiated by lightning such that the field propagation from the lightning sources to the recording site was entirely over saltwater.[29] The instrumentation system was arranged generally as indicated in Figure 9 and described in Reference 27. The amplitude spectra of E signatures were computed using the FFT on 128 or 256 equally spaced samples of manually digitized E records. Field amplitude spectra were derived from FFT of dE/dt records using the relation $F[E(t)] = F[dE(t)/dt]/i\omega$.

The electric radiation fields produced by lightning return strokes, stepped leaders, and intracloud discharge processes were also Fourier spectrum transformed. The results, adapted from Reference 29 to permit the data to be shown on a single graph, are presented in Figure 12. The spectra for return strokes (shown as the solid lines in the figure) show an f^{-1} frequency dependence from 100 kHz to 2 MHz, an f^{-2} dependence between 2 and 10 MHz, and an f^{-5} decrease above 10 MHz. In the 1 to 20 MHz range, the spectra of the initial fast transition in return strokes, the initial fast-rising portion of leader steps, and the fast transitions in positive intracloud flashes are very similar.



SOURCE: Reference 29

FIGURE 12 LIGHTNING SPECTRAL AMPLITUDES FROM INDIVIDUAL LIGHTNING PROCESSES

Since all the lightning signatures used in generating the spectra of Figure 12 were recorded at distances of 50 km or less over seawater, the effects of propagation on the lightning amplitude spectra below about 10 MHz should be minimal. The 3 dB upper limit of the dE/dt recording system was about 35 MHz; therefore, it would appear that the f^{-2} decrease of all spectral amplitudes between about 2 and 10 MHz is an intrinsic property of the individual lightning sources rather than an artifact of the instrumentation or propagation. (In this regard, it should be noted that Weidman and Krider make their measurements with the receiving antenna mounted on top of a large van. The possible electromagnetic effects of the presence of the van at the high frequencies where its dimensions are an appreciable fraction of a wavelength should be evaluated.)

The more rapid decrease in all spectral amplitudes above about 10 MHz may possibly be due to the effects of propagation, which unfortunately depend on the state of the sea surface, or this decrease may represent an intrinsic characteristic of the lightning sources. Since the spectra of the fast transitions in return strokes, leader steps, and intracloud discharges are all very similar in both amplitude and shape above about 2 MHz, the physical causes of these features in the different discharge processes may be very similar.

It is of interest to compare the spectra obtained from modern broadband measurement of individual lightning processes shown in Figure 12 with the lightning flash spectra obtained earlier using narrowband receivers and shown in Figure 7. The two sets of data have been plotted together for comparison in Figure 13. At low frequencies, the data are in good

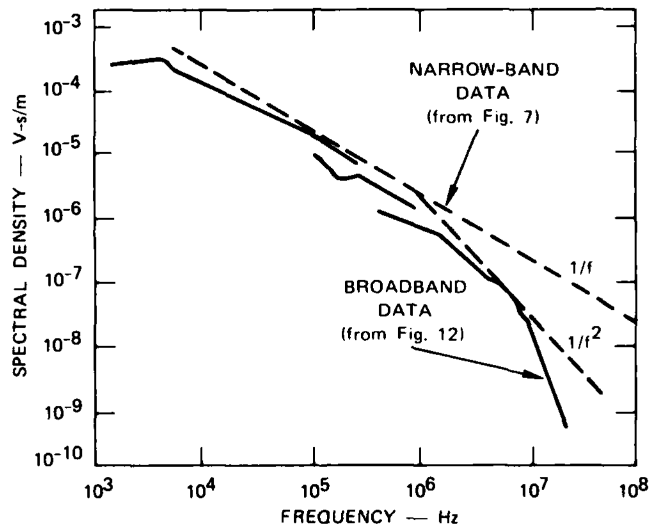


FIGURE 13 COMPARISON OF SPECTRA OF MAJOR SINGLE LIGHTNING EVENTS WITH NARROWBAND LIGHTNING SPECTRAL DATA

agreement, regarding both spectral amplitude and the 1/f dependence on frequency. However, above about 1 MHz, the broadband data indicate that the major individual processes associated with both cloud-to-ground and intracloud flashes have substantially less high-frequency content than one might expect from the 1/f curve drawn on the narrowband data in Figure 7. (The $1/f^2$ curve drawn on the narrowband data in Figure 7, however, is in good agreement with the broadband measurements.)

As indicated in Section II-C, a rationale for explaining this difference in spectral behavior may be devised as follows: To the narrowband system, the lightning flash has the appearance of Figure 2, where it will be recalled that 48,000 discharge events were observed during the roughly 1 s flash. The modern broadband studies, on the other hand, have concentrated on selected individual major lightning processes such as those shown in Figure 3. In general, the VHF signals observed during a lightning flash appear to be associated primarily with the probing activity in the cloud prior to and in conjunction with the development of the stepped leader and also between successive strokes.[22] This probing activity involves the occurrence of numerous short sparks ($\approx$ 1 m long) with little total energy compared to one of the major processes, but with a frequency spectrum extending well into the VHF as the result of the speed with which these small sparks can occur. Thus, the narrowband system sees the sum of the spectra of a single return stroke plus hundreds or even thousands of the probing discharges.

The results of summing two diverse spectra of this general sort have been explored analytically; the results are presented in Appendix B. In general, it is found that the rich high-frequency content of the numerous small pulses has the effect of adding substantially to the HF portion of the narrowband lightning spectrum. In other words, as indicated earlier, narrowband spectral measurements tend to meld together into a single curve the wide diversity of processes occurring during a lightning flash. This procedure was entirely satisfactory when practical concern was confined to the effects of the lightning signal on narrowband radio receiving systems. Presently, however, wideband digital avionic systems that are susceptible to transient pulses are of principal concern.

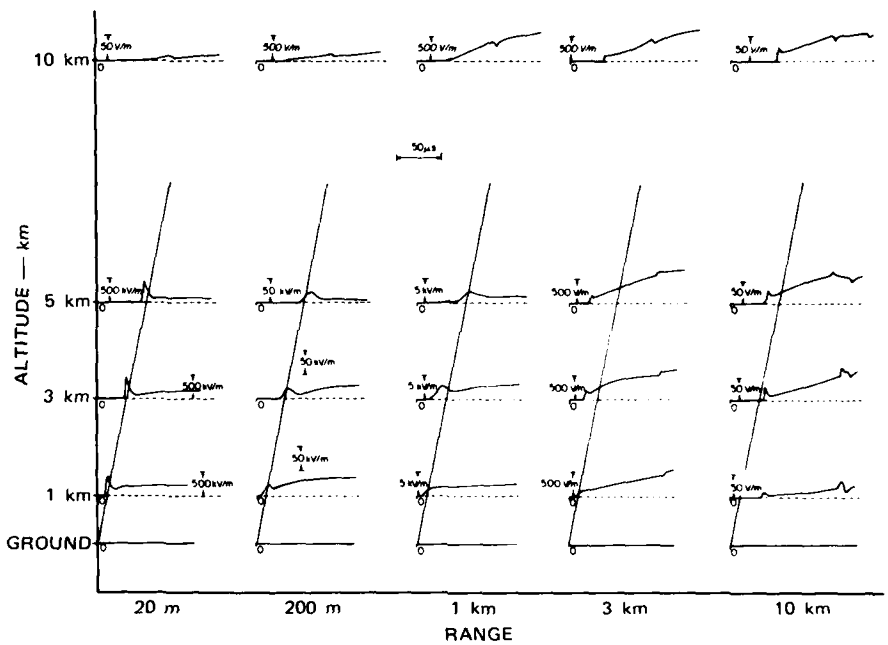
To analyze the effects of lightning on modern avionic systems, it is necessary to know the properties of the various individual pulses generated during the flash to determine how these signals couple to critical digital circuits. Using narrowband data for this purpose is complicated, because to unravel the data it is necessary to know the characteristics of the measuring system and the pulse repetition frequency of the lightning processes recorded.

C. CHANNEL CURRENT MODELING

For the past decade, Uman and Krider, together with their students, have worked systematically at deriving the characteristics of the lightning source from time-domain measurements of the radiated electromagnetic field.[30,31] In their approach, a temporal and spatial form for the channel current is assumed and then used to calculate the remote fields. The assumed current is constrained in its characteristics by the properties of lightning currents measured at ground level and by the available data on the measured electric and magnetic fields. The validity of the model is judged by how well the assumed current agrees with ground-based current measurements, when available, and how well the calculated remote fields compare with measured fields.

Uman and Krider have carried out their own ground measurements of lightning fields to provide the data they need to validate their channel current models. These measurements have been carefully carried out, but have not included measurement of electromagnetic fields in the vicinity of the lightning channel at aircraft altitudes.

Typical results of this recent work are presented in Figures 14 and 15, showing the predicted horizontal electric field as a function of altitude and distance from the lightning return stroke channel. These data are of particular interest in that they indicate the way in which the channel model is tested and naturally evolves. They also indicate the rapidity with which lightning models are evolving and demonstrate the continuing need for good experimental data.

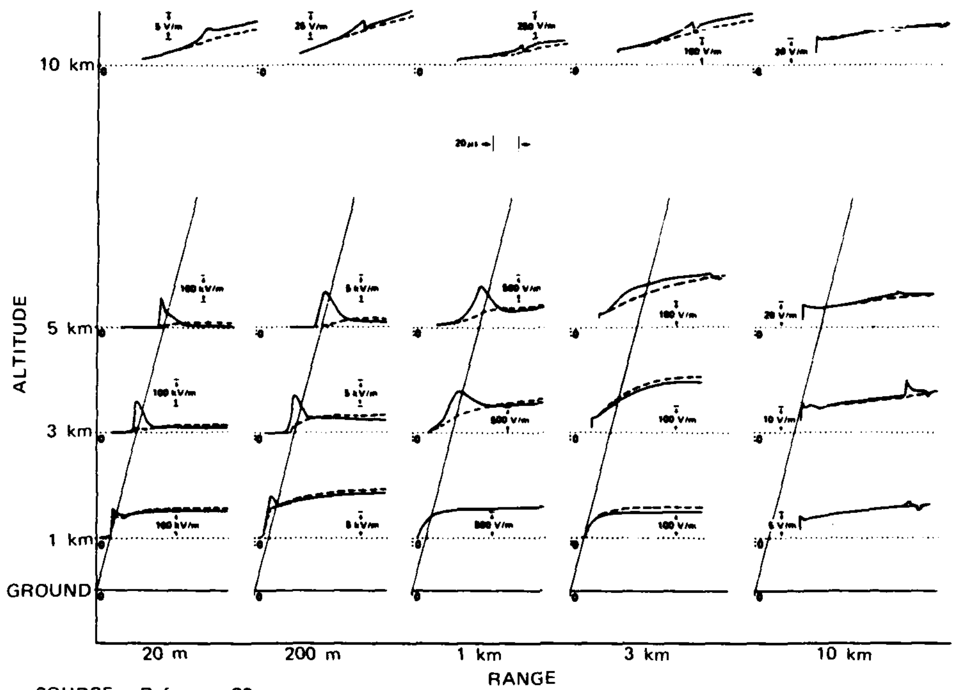


NOTE: Channel Length = 7.5 km
Peak Stroke Current = 15 kA
Ground Conductivity = ∞

SOURCE: Reference 30

FIGURE 14 HORIZONTAL ELECTRIC FIELD

The results in Figure 14 were calculated assuming a peak return stroke current of 50 kA and were published in 1980.[30] The calculations were based on the model of Lin et al.,[31] which postulates that the return stroke current is composed of three components: (a) a short-duration upward-propagating pulse of constant magnitude, waveshape, and velocity that is associated with the electrical breakdown at the return-stroke wavefront and that produces the fast peak current; (b) a uniform current which is already flowing in

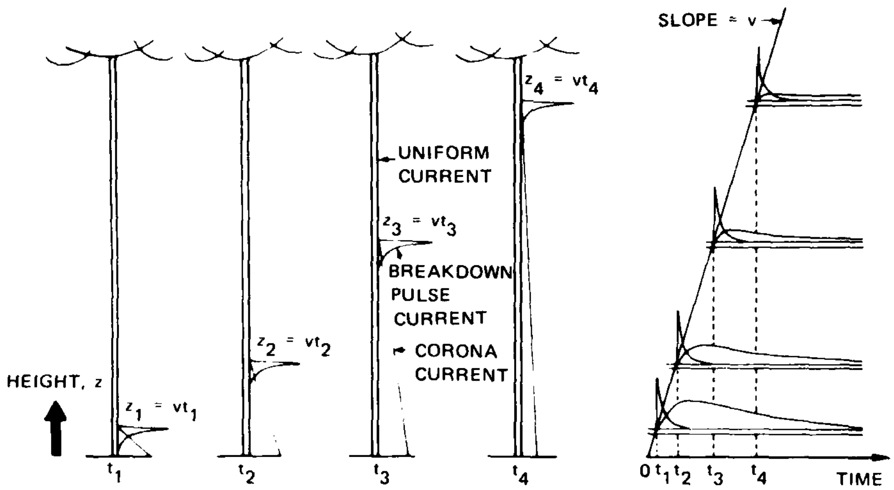


SOURCE: Reference 32

FIGURE 15 CALCULATED HORIZONTAL ELECTRIC FIELDS FOR A TYPICAL SUBSEQUENT RETURN STROKE. Solid lines calculated using Lin model of Reference 31. Dashed lines calculated using Master model of Reference 33.

the leader channel (or which may start to flow soon after the commencement of the return stroke) and (c) a "corona" current which is caused by a flow of charge radially inward and then downward and which removes the charge initially stored in the corona sheath around the leader channel after the passage of the return-stroke wavefront. These three current components are illustrated in Figure 16.

The results in Figure 15 assume a peak current of 15 kA and were published in May 1982.[32] Comparing Figures 14 and 15, we see that the time structure of the corresponding solid curves is the same. (The amplitudes are higher in Figure 14 because a higher peak current was assumed.) Figure 15, however, includes a set of dashed curves that were calculated using a model of Master,[33] which assumes that the amplitude of the initial breakdown pulse diminishes with increasing altitude. This modification in the physical model of the lightning channel obviously has a major effect on the radiated field predicted at the higher altitudes. In particular, the high-amplitude, sharp leading edge of the radiated pulse is eliminated at the short ranges of greatest interest to aircraft coupling.



SOURCE: Reference 30

FIGURE 16 CURRENT DISTRIBUTION FOR THE MODEL OF Lin et al. (Reference 31) IN WHICH THE BREAKDOWN PULSE CURRENT IS CONSTANT WITH HEIGHT. v = constant velocity of the breakdown pulse current. Current profiles are shown at four different times, t_1 through t_4, when the return-stroke wavefront and the breakdown pulse current are at four different heights, z_1 through z_4, respectively.

Two observations formed the basis for the modification of the Lin model[31] by Master et al.[33] First, subsequent strokes were formerly thought to have both luminosities (and therefore, currents) and velocities that were constant with height. However, Jordan and Uman[34] recently found that the peak luminosity of subsequent strokes decreases to half the initial peak in less than 1 km above ground. The implication of this observation is that the breakdown pulse current ([a] in the Lin model above) must also decrease with height.

Secondly, when the breakdown pulse reaches the top of the channel, the model predicts a field pulse of opposite polarity to that of the initial field with a waveshape that is a "mirror image" of the initial field. Mirror images are observed occasionally in the fields from first return strokes, but almost never in the fields from subsequent return strokes. This experimental observation is reasonable if the breakdown pulse current decays with height so that it has a negligible effect when it reaches the end of the channel.

In view of these observations, Master et al., proposed the following modification to the Lin model: the breakdown pulse current is allowed to decrease with height above ground, but all other features of the original model remain unchanged. The fields at ground level produced by this new model are essentially the same as those of Lin et al., except for the absence of the "mirror image." The fields in the air, however, differ considerably, especially at close ranges.

Thus, although the channel-modeling activity of Uman and Krider is highly important and should be encouraged, we should also note that it is still evolving. Accordingly, it would be premature to base major decisions on these predictions unsupported by in-flight experimental corroboration. In light of the importance of having available an accurate lightning channel model, every effort should be made to obtain in-flight data regarding the fields in the vicinity of the return-stroke channel.

D. LIGHTNING-TRIGGERING EXPERIMENTS.

The unpredictability of lightning has meant that, historically, lightning experimenters have generally had to content themselves with studying lightning from a distance. Direct measurement of lightning current was largely confined to strikes occurring to instrumented towers or structures on tall buildings, which are known to trigger lightning. That lightning can also be triggered by a fine conductor was demonstrated tragically in 1752 when Russian physicist G. W. Richmann was killed attempting to repeat Benjamin Franklin's experiments, which had demonstrated the connection between lightning and static electricity.[35]

In 1961, Marx Brook and his coworkers suggested that lightning could be triggered by a wire rapidly introduced into the region of high electric field beneath a thundercloud.[36] M. M. Newman pursued this suggestion and succeeded in triggering lightning strikes to his research ship at sea by firing wire-trailing rockets from a special instrumented platform located on the ship.[37]

Efforts were made to trigger lightning over ground, but were not successful for a long time. Corona discharges from pointed objects on the ground tended to reduce the field intensity beneath the cloud. Also, it was found that the high-impulse rockets used in these experiments tended to break the trailing wires before they attained sufficient altitude.

Beginning in the 1970s, French experimenters pursued the problem of lightning triggering and evolved a successful system based on an antihail rocket, manufactured by Ruggieri.[38,39] As the rocket climbs, it unspools a fine wire encased in a container on the ground. Beginning in 1981, the French scientists teamed with researchers from the Air Force Weapons Laboratory (AFWL) and the Air Force Flight Dynamics Laboratory (AFFDL) for a series of triggered-lightning experiments at Mt. Baldy in Socorro, New Mexico.[40,41] In addition to the rocket-launching system, the French experimenters' instrumentation includes a set of ground-based field meters. By waiting until the field intensity measured on the ground was $>$ 10 kV/m, they were successful in triggering lightning on virtually every rocket firing.

A ground-current-measuring "cage" is included in the experimental setup to record the waveform of the triggered lightning stroke.

An interesting feature of the experiment, provided by AFFDL, is a large aluminum cylinder (simulating an aircraft fuselage) mounted vertically in an insulating cradle. Lightning strikes are triggered to the top of the cylinder. The circuit to ground is completed by a discharge from the lower end of the cylinder to the ground-current-measuring cage. The cylinder is equipped with external sensors to measure currents and fields on its exterior. Provisions are included in the design of the cylinder to generate apertures in the skin so that signals will be induced in the interior. Sensors are available to measure fields on the inside and currents induced on wiring installed on the interior. Tests with the cylinder have been carried out, but results have not been published to date. Analysis of these measurements will be very important for the aircraft interaction problem.

An interesting innovation was added to these experiments by replacing the lower portion of the triggering wire with a dielectric filament. In this way, lightning flashes are triggered by upward and downward propagating leaders from the two ends of the wire. During the triggering experiments, the AFWL operated a variety of high-speed recorders housed in an underground bunker "kiva" in the vicinity of the triggering site.

Testing by the French and AFFDL scientists is projected to continue in the future--possibly with the test site relocated to Florida. The AFWL is developing its own triggering capability and plans to continue testing at Socorro.

E. AIRBORNE MEASUREMENTS.

1. General.

Within the past six years, various flight test programs to study lightning and its interaction with aircraft have been undertaken, are under way, and are being planned. The first of these, using a Learjet test aircraft, was conducted by SRI, the Air Force, and NASA in the vicinity of KSC and Patrick Air Force Base, Florida.[42,43] These tests were designed to take advantage of the availability of an aircraft instrumented by SRI for launch support activity in the vicinity of thunderstorms at KSC. The lightning measurements were intended to investigate the feasibility of using modern instrumentation and sensors to make airborne measurements of lightning-related fields, and to generate data on the transients generated on the aircraft and its interior wiring. The test program demonstrated the feasibility of operating in the vicinity of active thunderstorm cells with modern high-speed instrumentation. The tests also corroborated the need for careful sensor design and placement to yield unambiguous data. The difficulty of finding ideal lightning conditions indicated that it would be prudent to expect that a substantial number of flight tests would be required to generate the desired quantity and variety of airborne data.

2. NASA F-106.

Since 1980, Pitts and his coworkers have operated an instrumented F-106 in active thunderstorm cells in an effort to gather data on direct strikes to the aircraft.[44,45] During 1980 and 1981, the F-106 was flown at an altitude of 15,000 to 16,000 ft with the expressed intention of intercepting attached strikes. During this period, a total of 20 attachments were recorded. The largest peak current observed was 15 kA, and the largest value of dI/dt was 2.2 x 10^{10} A/s. Results of these first two years of activity are summarized in two papers.[46,47]

During the summer of 1982, and after consultation with atmospheric physicists, the F-106 was flown at altitudes of 25,000 to 35,000 ft, again with the express intention of experiencing direct attachments. Provisions were also made during this flight period to use a VHF ground radar to locate active regions within the cell and to guide the aircraft to them. At this altitude, a total of 141 strokes attached to the aircraft. The largest peak current observed was 10 kA, and the largest value of dI/dt observed was 8.8 x 10^{10} A/s. The instrumentation on the F-106 was such that the triggering system produced a bias in the measurements, i.e., there was a "dead time" during which the majority of the flash sequence for each single attachment was not recorded. Data from the 1982 measurements are being analyzed, and a report will be issued shortly.

Throughout this period of activity, the F-106 instrumentation has systematically been upgraded, principally by increasing the channel capacity of the recording system. In addition, tests and analyses have been made of the natural responses of the aircraft and its sensors to transient disturbances.[48] Thus, this team is prepared for very efficient data recording and analysis during the next thunderstorm season.

3. Air Force WC-130.

Between 1979-1981, the U.S. Air Force operated an instrumented WC-130 aircraft in the vicinity of thunderstorm cells as part of a study of lightning characteristics.[49,50] The purpose of these tests was not to study direct strikes to the aircraft, but to investigate the characteristics and effects of nearby lightning. The test aircraft, instrumented for lightning interaction studies, was flown in the vicinity of thunderstorms. The aircraft was usually flown at 15,000 ft MSL, but some data were collected at 1,500 to 8,000 ft MSL. The aircraft contained a variety of sensors located at various positions on the fuselage. The onboard instrumentation system gradually evolved and ultimately included 10 channels with 20 MHz bandwidth (using transient digitizers). Simultaneous ground-based measurements were obtained, including a VLF system to locate the lightning relative to the aircraft. The aircraft belonging to the National Oceanographic and Atmospheric Administration (NOAA) was not flown with the intention of intercepting direct hits. Most of the data were obtained with the aircraft in the far field of the observed strokes (5 to 35 km range). The average risetime of the surface fields was approximately 200 ns.

FFT calculations were carried out for the recorded waveforms. The spectral amplitude decreased as $1/f$ up to a frequency of about 2 MHz and as $1/f^2$ above 2 MHz. This behavior is consistent with the results of ground measurements shown in Figure 12.

During the 1981 test program, the aircraft experienced two instances of direct attachment of a discharge. The measured peak currents that attached to the aircraft were 600 A and 3,000 A for these two instances. The aircraft was flying at an altitude of 16,000 ft at a speed of 333 km/h, in an area of slushy precipitation (outside air temperature was +5°C). The effects of these two direct strikes to the aircraft were as follows: the larger stroke broke the VHF antenna located above the fuselage and produced 12 burn scars located on the top portion of the fuselage and spread over a distance of 80 ft. The second stroke dumped the memories of two of the internal aircraft computers. Electric fields at the wing tips at the time of these strikes were as large as 200 kV/m.

Approximately 60 to 70 percent of the data had been processed at this time. A report describing these data is in the final stages of publication and will be available through AFFDL.

4. French Transall.

The French Office National d'Etudes et de Recherches Aerospatiales (ONERA) has assembled and flight-tested an instrumentation system for lightning testing using the Transall aircraft. The system includes the following sensors and instruments:

- Current probes on front and rear booms responding to amplitudes of ±150 kA with a bandwidth of about 3 MHz.
- Four field mills to provide charge on the aircraft and atmospheric electric field. A real-time display of the field and its direction is used to vector the plane into high-field regions where the probability that it will be struck is high.
- Electric and magnetic field sensors inside and outside a window on the aircraft surface. Induced voltages on three wires inside the window (one short-circuited, two terminated in 50 Ω can also be measured). The signals are sampled by four Tektronix transient analyzers with 10 ns resolution. Most signals are recorded on tape by means of two 3 MHz video recorders, two 14-channel 400 kHz tape recorders, and two 10 MHz magnetic tape recorders. The digital records are registered with 1,500 pre-trigger points at 10 ns intervals and 500 post-trigger points at 50 ns. Several additional magnetic field measurements can be made on the aircraft surface and transcribed on the 400 kHz tape recorder.
- Sensor for mesurements of precipitation charging on a special insulated windshield.
- Film and TV camera photographs of the lightning strikes.

- Photoelectric sensors for measurements of the light impulses from the tip and front of the fuselage.

Most analog data are transmitted from the current or field sensors through fiber-optic links that have a dynamic range of 41 dB and a bandwidth from 500 Hz to 180 MHz.

Extensive mockup testing and instrument calibration have been completed, and a shakedown test of the instrumentation on the Transall aircraft has been carried out. During the shakedown tests over France, the aircraft was struck by lightning, and some data were recorded. Unfortunately, ONERA personnel feel that there is some question regarding calibration and are unwilling to release the lightning strike data until the questions have been resolved. Since the test aircraft was needed for other programs, no in-flight lightning testing was carried out by ONERA during 1982, and none is planned for 1983.

IV TRANSIENT ELECTROMAGNETIC INTERACTION WITH AIRCRAFT

A. COUPLING MECHANISMS.

Electromagnetic fields of lightning and EMP interact with aircraft to produce transient surface currents and surface charge densities on the metal fuselage. Transients are induced at subsystem interfaces and ultimately at equipment terminals inside the aircraft. While lightning and EMP differ in several important particulars, there is an important similarity in their interaction with aircraft -- namely, they are impulsive sources and they provide a relatively broadband excitation of the aircraft.

The aircraft responds at all the natural frequencies of the aircraft structure and of the internal wiring harnesses. The amplitudes of the induced responses are determined by the source amplitudes at these natural frequencies and by an appropriate coupling transfer function. In the time domain, these responses can be approximated as sums of damped sinusoids of several characteristic frequencies.

1. EMP Interaction at External Surface.

Interaction of an EMP with an aircraft's metallic skin has been studied extensively in the past decade.[51] The EMP strikes the aircraft and produces transient fields at the aircraft skin. The tangential magnetic field at the surface is related to the current density flowing in the aircraft skin, and the perpendicular electric field at the skin is related to the surface charge density. From electromagnetic theory, these transient surface fields can be considered as equivalent sources for current and voltage transients that are induced on equipment wiring inside the aircraft.

The exact spatial and spectral distributions of the surface fields are very complicated for an actual aircraft. The transient waveforms of the surface current and normal electric field are combinations of damped sinusoids, with frequencies determined by the lengths of aircraft structural elements. Because the pulsewidth may be less than the transit time across large aircraft, the current may also behave as a discrete pulse reflecting back and forth. The peak values of the surface currents are small near the ends of the wings and fuselage and have their largest amplitudes near the center of the aircraft at the fundamental frequencies. The perpendicular electric field at the surface is largest at the ends of the structure and smallest near the center at the fundamental frequencies.

Thus the surface fields on aircraft illuminated by EMP will vary with location and will have a damped sinusoidal time dependence. The fundamental frequencies of the surface fields will be associated with the lengths of structural elements -- from 1 MHz to 20 MHz for most aircraft. Significant energy is present at higher frequencies, especially at multiples of the fundamental resonances.

2. Lightning Interaction with Aircraft.

Interaction between lightning and an aircraft in flight is a very complex problem that is still not well understood. Many aspects of this problem are summarized in an IEEE special issue on lightning and aircraft.[52] Two basically different interaction modes can be identified: (1) field interaction with distant (unattached) flashes, and (2) interaction via direct attachment of a flash to an aircraft.

Interaction with Radiated Fields of Unattached Stroke. Electromagnetic coupling of a distant (unattached) stroke to an aircraft is similar in some respects to EMP interaction with aircraft. The aircraft again responds as a receiving antenna, with damped sinusoidal currents induced on the external surface. The peak amplitude of the induced surface current varies with location on the aircraft, being small near the ends of the aircraft (nose, tail, wingtips) and having larger peak values at locations away from the ends. The fundamental ringing frequencies of the damped sinusoids are again related to the aircraft structural dimensions.

Direct Attachment of Lightning to Aircraft. The most severe lightning-related threat is the direct attachment of lightning to the aircraft. This can occur coincidentally (as in the interception of a cloud-to-ground stroke by an aircraft), or the attachment may be triggered by the presence of the aircraft in the charged environment. Triggered attachments are believed to occur much more frequently than coincidental attachments, and both the probability of attachment and the nature of the attached current vary with altitude. It is highly probable that all measured strokes to instrumented aircraft have been of the triggered variety.

The time history of the attached current is not understood in great detail at this time. The few measurements available indicate that the attached current consists of hundreds to thousands of pulses per attachment, with a wide variety of pulse shapes and amplitudes. The peak currents observed in aircraft measurement programs have been typically less than 15 kA, and the largest peak time derivative measured in flight to date has been less than 10^{11} A/s (as discussed in Section III-E in connection with the 1982 tests with the NASA F-106).

Direct attachment results in a spatial distribution of the surface current that differs greatly from that induced on the aircraft by EMP or distant lightning. Attachment produces a relatively uniform distribution of surface current between the attachment points, as compared to the complicated spatial distribution associated with EMP or with unattached lightning. The waveshape of the surface current will be some combination of the attached current waveshape and damped sinusoids associated with reflections from the attachment points and with field excitation of structural members (e.g., excitation of wing resonances by nose-to-tail attachment). The composite waveform will be dominated by the attached current waveshape for locations between the attachment points, and the current density can be very high near the attachment points.

It must be noted strongly here that direct attachment of lightning to aircraft is not well understood at all. The descriptions of the environment given in the previous paragraphs are based on a small data sample. These data indicate that the complete electromagnetic environment at an aircraft during an attachment is extremely complex.

3. Internal Wiring Transients.

The fields at the surface of an aircraft can be used as equivalent sources for currents and voltages induced in interior wiring. In theory, at least, one can predict the voltage and current on each wire, given the external surface field distribution and the wiring and structure geometry. This problem cannot be solved in practice because of the complexity of the wiring harnesses and cable configurations in modern aircraft. Although accurate quantitative predictions of interior transients are not possible, several qualitative statements can be made:

- Interior voltages and currents will have a multiple damped sinusoidal response, with the ringing frequencies associated with wiring lengths, termination impedances, and distributed parasitic and mutual impedances.
- The predominant internal response frequencies (extending to 20 MHz and above) are found to be higher than the external resonances, which are in the range of 1 to 10 MHz for most aircraft.
- The amplitudes of the internal responses are related to complex combinations of the external surface fields and their derivatives.
- The duration of the damped oscillation on internal wiring typically will be less than a few microseconds.

Figure 17 contains an example of this type of response. The figure shows the time history and spectrum of the current induced at the terminals of a digital data processor used on an aircraft. This current was measured while the aircraft was being excited by a simulated EMP environment. This basic type of response (i.e., oscillations at the natural frequencies of the circuit in response to an impulsive excitation) is typical of that induced on aircraft wiring by EMP. The peak amplitude of the induced current is a strong function of the energy in the source at the frequencies of interest -- above approximately 20 MHz for most aircraft. In particular, it should be noted that, if the driving source

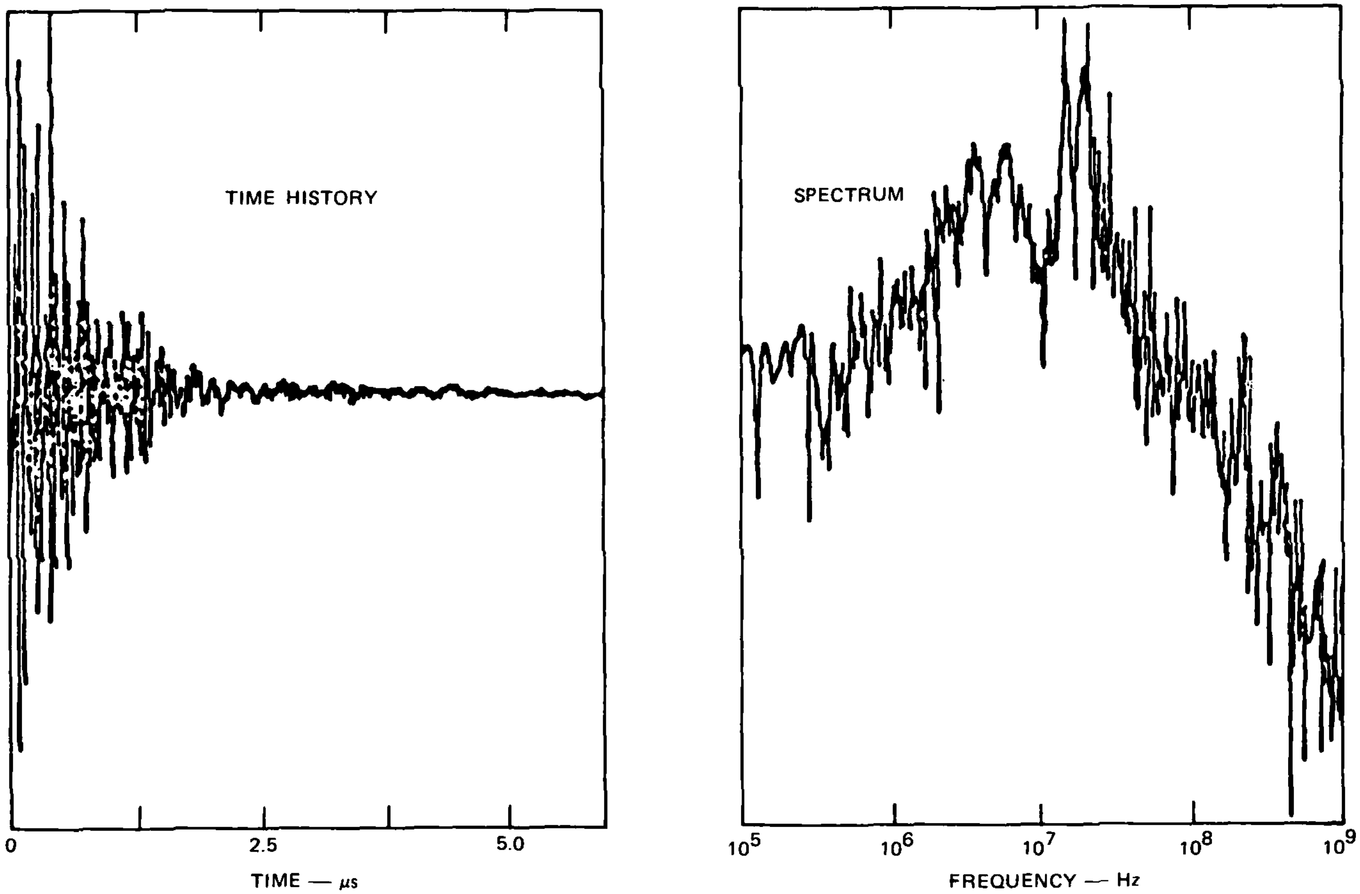


FIGURE 17 EXAMPLE OF TRANSIENT CURRENT INDUCED AT DIGITAL PROCESSOR TERMINALS BY SIMULATED EMP INCIDENT ON AIRCRAFT

contains no energy at the internal response frequencies (and if the system remains linear), there will be no internal response at those frequencies.

The internal response of the aircraft to a lightning environment is qualitatively similar to Figure 17, except that the induced current consists of a sequence of damped transients of the sort illustrated, where each internal transient is induced by each of the individual pulses that make up the complete flash. It should be noted that the internal response will have died out completely before the arrival of the next pulse. The peak amplitude and the waveshape of each of these internal current pulses will be a strong function of the spectrum of the individual pulse which excited the transient. Again, if the lightning- driving pulse source contains no energy at the internal response frequencies (and if the system remains linear), there will be no internal response at these frequences.

B. EXAMPLES OF ELECTROMAGNETIC INTERACTION WITH AIRCRAFT.

The interaction of an electromagnetic wave with a metal aircraft results in transient currents flowing on the fuselage and on wire penetrations of the fuselage (e.g., wire antennas, fuel lines, hydraulic lines), as well as field coupling through apertures and seams on the structure. The interior wiring is strongly excited by the transients entering on wire penetrations and through apertures, and very weakly excited by fields that diffuse through the metal skin.

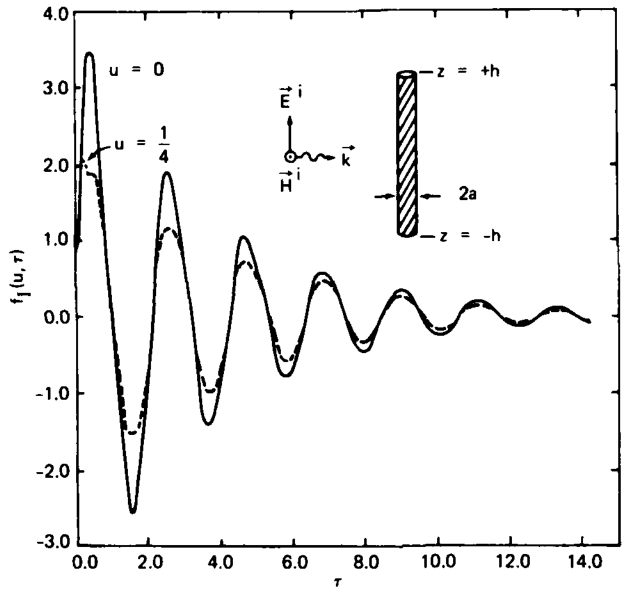
The external interaction problem is well understood for aircraft in the far field of a lightning flash or in the presence of the plane wave EMP.[51] Coupling to an aircraft in the near field of a flash and direct stroke attachment are not well understood at this time.[53] The internal interaction problem is very complex, and the level of understanding is such that only worst-case coupling predictions can be made for certain well-defined configurations.[54]

In the remainder of this section, several examples are presented to indicate the important issues associated with this problem. Consider a hollow metal cylinder with a 20 m length and a 1 m radius. The cylinder is assumed to contain a circular aperture of radius 0.15 m (6 in.) located midway between the ends of the cylinder. The transient current induced on the outer skin interacts with the aperture, resulting in magnetic fields which interact with the interior. Recent research[54] has indicated that the largest voltage that can be induced on any single-turn loop inside the cylinder is proportional to the peak time derivative of the external skin current density. This voltage has a peak value given by

$$V(\text{peak}) = 2\mu_o r_a^2 \dot{J}_p \quad ,$$

where r_a is the aperture radius, μ_o is the permeability of air, and $\dot{J}_p$ is the peak value of the derivative of the external skin current density. The exact wave shape of the loop voltage depends on the loop length, the loop's proximity to conducting surfaces, the termination impedance, and the external skin current waveshape. Let us now analyze the behavior of this system when it is driven by selected transient pulses covering a range of pulse parameters to explore the effects of these source characteristics on the signals induced in the internal loop.

First, consider the case of a unit-step plane wave exciting the cylinder with the incident electric field parallel to the cylinder axis and with the direction of propagation normal to the axis. Figure 18 shows the waveform of the current on the skin. The horizontal axis of the figure is normalized as shown, and the vertical axis is normalized as discussed in Reference 51. The curve shows that the skin current response is dominated by



NOTE: To obtain actual peak amplitude, multiply ordinate by the factor:

$$\frac{LE^i}{120\pi \ln(L/4a)}$$

where E^i is the peak value of the incident electric field

SOURCE: Reference 51

FIGURE 18 NORMALIZED AXIAL CURRENT FOR A UNIT-STEP INCIDENT PULSE ($u = z/L$, $\tau = ct/L$, $L = 2h$)

ringing at a frequency related to the cylinder length. For the cylinder discussed here ($L = 20$ m), the ringing frequency is about 7.5 MHz. This curve is derived for a unit-step incident field, and is also a good approximation for incident pulses with rise times much shorter than L/c and fall times much larger than L/c.

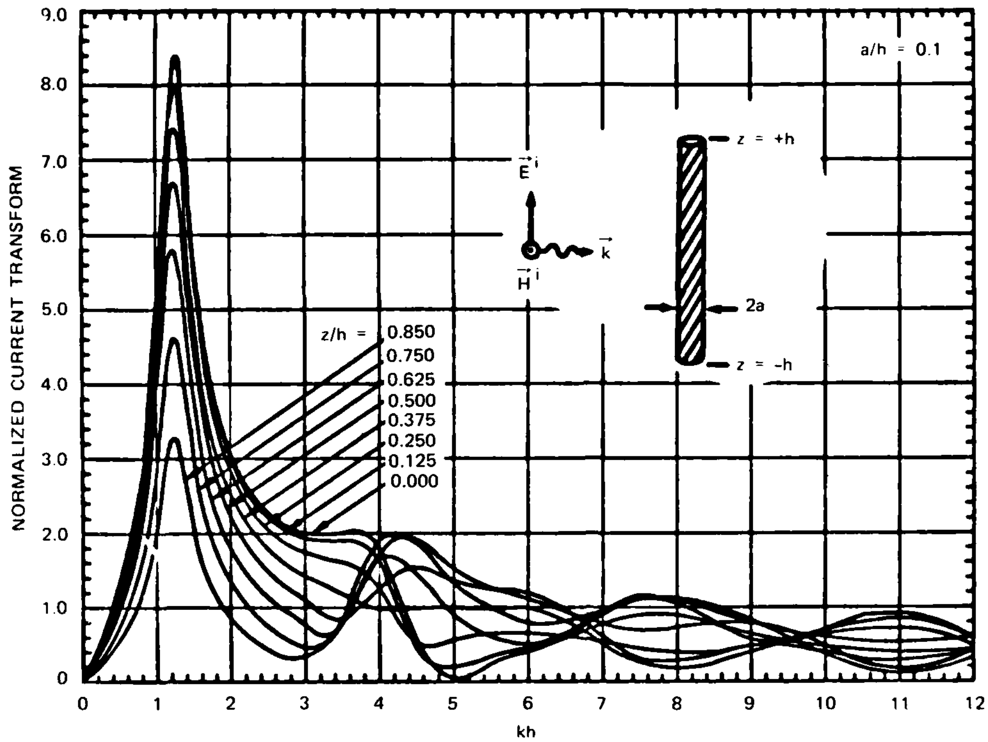
Now consider two incident pulses, each with fast rise times characteristic of EMP (about 3.5 ns for the 10%-90% rise time).[55] One pulse has a pulsewidth of approximately 200 ns, which is similar to that of the double exponential pulse, and the other pulse has a width of approximately 20 ns, which is shorter than the transit time of current pulses along the cylinder. The peak value of the induced surface current density and the peak derivative can be estimated directly from Figure 18, since the rise time of both pulses is much smaller than the transit time ($L/c = 67$ ns) along the cylinder. If the peak amplitude of the incident field is 50 kV/m for each of the two pulses, the peak current at the center of the cylinder is about 5.8 kA, and the peak time derivative is about 1.7×10^{11} A/s. The skin current density, J_p, and its derivative, are estimated by dividing the current, and its derivative, by the circumference of the cylinder. This result can be inserted into the above equation to obtain a peak voltage of about 1.5 kV induced on a large loop placed directly behind the aperture.

The effect of the differences in the incident pulsewidth can be observed at later times. The wider of the two pulses ($\approx$ 200 ns) looks like a step function to the 20 m cylinder, and the narrower pulse ($\approx$ 20 ns) resembles an impulse function. Thus, the response to the 200 ns pulse is similar to that of Figure 18, while the response to the 20 ns pulse has the same peak amplitude but with a somewhat different waveshape after the peak.

The point of this example is to show that the <u>peak amplitudes</u> of induced skin currents and, subsequently, of internal voltages induced via aperture coupling are determined by the leading edge of the incident field pulse. For the two fast pulses considered above (where the rise time is much less than the transit time along the cylinder), the peak amplitudes of the induced voltages were equal, and only the late time portion of the response was affected by the incident pulsewidth.

Next, consider two incident field pulses similar to those launched by cloud-to-ground lightning. The width of each pulse is assumed to be 40 μs, and the rise times are 100 ns and 1 μs, respectively. The peak field amplitudes are assumed to be 50 kV/m. The rise times of the incident pulses are each larger than the transit time along the cylinder. This implies that the induced surface current is still rising when the first reflections appear from the ends of the cylinder. Thus, the skin current does not reach the same peak value that was reached with the faster pulses discussed earlier.

These interaction problems with slow rising pulses can be solved rigorously by using the incident field spectra with the step response transfer function shown in Figure 19. An approximate evaluation of the peak skin current can be made from simple time-domain considerations. Assume that the 100 ns rise time pulse is incident on the cylinder. The peak in the time domain occurs when the reflection from the ends of the cylinder arrive at the center point. This occurs at $t = 0.5\ L/c$, or 33 ns for a 20 m cylinder. Thus, only the

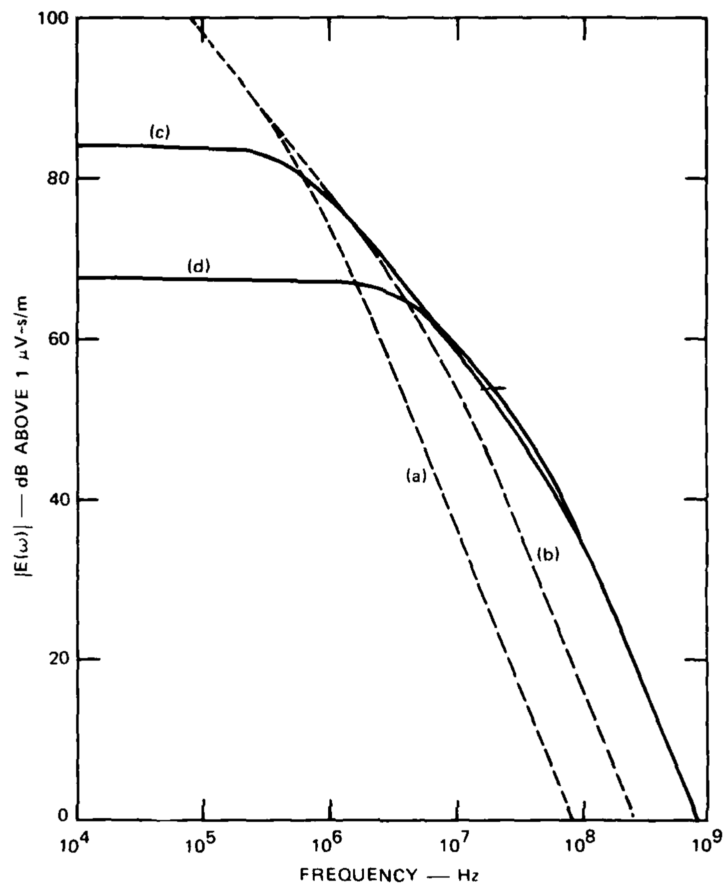


SOURCE: Reference 56

FIGURE 19 MAGNITUDE OF THE CURRENT ON A CYLINDER SCATTERING A PLANE WAVE vs kh WHERE k = 2πf/c AND h = L/2

first third of the leading edge of the 100-ns rise time pulse contributes to the peak skin current. Then, as a first approximation, the skin current density excited by the 100-ns rise time pulse is only about one-third of that excited by the faster rising EMP-like pulses discussed earlier. The skin current excited by a 1 μs rise time pulse is even smaller, as only about one-thirtieth of the incident pulse contributes to the rise time before reflection occurs.

These calculations must be considered as first-order approximations, but the results indicate the importance of the fast-rising part of the incoming wavefront on the peak voltages and currents induced in aircraft wiring by fields penetrating apertures. This can also be seen in the frequency domain by comparing the spectra of four incident pulses similar to those discussed above. Figure 20 presents double-exponential representations of these spectra. The two lightning-like pulse spectra are shown in curves (a) and (b). Spectra for pulses with EMP-like rise times are shown in (c) and (d). It can be seen that, for the four example pulses discussed here, the faster-rising pulses excite responses above



(a) LIGHTNING-LIKE PULSE:
1-μs TIME TO PEAK
40-μs FALL TIME (to 1/2 peak)
5 x 10^6-V/m/s PEAK RATE OF RISE

(b) LIGHTNING-LIKE PULSE
100-ns TIME TO PEAK
40-μs FALL TIME (to 1/2 peak)
5 x 10^7-V/m/s PEAK RATE OF RISE

(c) EMP-LIKE PULSE--OLD DOUBLE EXPONENTIAL MODEL:
10-ns TIME TO PEAK
200-ns FALL TIME (to 1/2 peak)
5 x 10^8-V/m/s PEAK RATE OF RISE

(d) EMP-LIKE PULSE--NARROW DOUBLE EXPONENTIAL MODEL:
7-ns TIME TO PEAK
20-ns FALL TIME (to 1/2 peak)
5 x 10^8-V/m/s PEAK RATE OF RISE

FIGURE 20 DOUBLE EXPONENTIAL REPRESENTATION OF ELECTRIC FIELD SPECTRA FOR HYPOTHETICAL EMP-LIKE PULSES (solid lines) AND FOR HYPOTHETICAL LIGHTNING-LIKE PULSES (dashed lines) (50 kV/m peak amplitude in all cases)

10 MHz more strongly than do the wider and slower pulses. Responses below about 1 MHz are excited more strongly by the wider and slower pulses. In general, the rise time affects the high-frequency content. Increasing the rise time increases the high-frequency content. Changing the pulse duration changes the low-frequency energy content. Increasing the duration increases the low-frequency energy.

If a return stroke attaches directly to the cylinder, the resulting skin current is equal to the sum of the attached stroke current and the skin currents induced by the near fields of the stroke and by other nearby cloud processes. The near field interactions have not been analyzed sufficiently at this time, and their contribution to the total skin current is unknown. However, if it is assumed that only the return stroke current flows on the cylinder, the resulting internal voltages can be computed. For the sake of this example, the direct stroke current is assumed to have a peak amplitude of 100 kA and a rise time (to peak value) of 1 μs. The derivative of the skin current is then approximately 10^{11} A/s, which is about half of that induced by the fast EMP fields and which is equal to the largest derivative ever observed in instrumented flight programs.

The results of the calculations discussed here are consolidated in Table 1. These are first-order approximations because of the shortcuts discussed above. In addition, the hypothetical lightning fields were assumed to be plane waves, which do not have the same spatial distributions as do near fields; therefore, the results in Table 1 must be considered preliminary. However, they are indicative of the differences between the different types of impulsive noise sources encountered by military aircraft. The examples described here highlight the need for more information concerning lightning fields at frequencies above a few megahertz.

C. SUMMARY

This idealized example indicates the importance of the fast-rising component of external interference fields on the external surface field spectra and subsequently on the currents induced on internal wiring. The nature of an aircraft's response to impulsive excitation requires that any analysis of this problem pay close attention to the response frequencies and to the amplitudes of the external source spectra at these frequencies. Three distinct frequency ranges are important for coupling to aircraft:

- Below 1 MHz: Coupling to long-wire trailing antennas.
- 1 to 10 MHz: Resonances associated with external structural sizes (e.g., fuselage length, wing length).
- Above 10 MHz: Resonances associated with internal wiring transients, with resonant frequencies determined by wiring lengths, wire-to-wire and wire-to-structure impedances, and termination impedances (including lead inductance and parasitic capacitance).

Thus, it is apparent that the coupling of impulsive noise to aircraft is a very complex problem. Any comparison of the effects of lightning and EMP on aircraft must consider the source spectra and the transfer functions appropriate for the specific aircraft. These considerations must then be applied to all vulnerability modes of the aircraft, as described in the next section of this report. Given the complexity of the

TABLE I

Transients Induced by Lightning-Like and EMP-Like Signals

External Source Parameters	Peak Skin Current (kA)	Derivative (A/s)	Peak Internal Voltage (kV)*
Lightning-Like--(a) from Fig. 20:			
50-kV/m peak amplitude 1-μs time to peak 40-μs fall time (to 1/2 peak) 5×10^6-v/m/s peak rate of rise	0.06	1.7×10^9	0.015
Lightning-Like--(b) from Fig. 20:			
50-kV/m peak amplitude 100-ns time to peak 40-μs fall time (to 1/2 peak) 5×10^7-v/m/s peak rate of rise	1.9	0.6×10^{11}	0.5
EMP-Like Rise, *Old EMP Double* Exponential--(c) from Fig. 20:			
50-kV/m peak amplitude 10-ns time to peak 200-ns fall time (to 1/2 peak) 5×10^8-v/m/s peak rate of rise	5.8	1.7×10^{11}	1.5
EMP-like Rise, Narrow Pulse--(d) from Fig. 20:			
50-kV/m peak amplitude 7-ns time to peak 20-ns fall time (to 1/2 peak) 5×10^8-v/m/s peak rate of rise	5.8	1.7×10^{11}	1.5
Direct Stroke Attachment**			
100-kA peak 1-μs time to peak	100	1.0×10^{11}	0.88

* Associated with 0.15-m circular aperture.

** Assumes no field interaction, only current injection.

aircraft's response and the variety of its vulnerability modes, it is apparent that hardening of an aircraft for both lightning and EMP requires consideration of both environments. A hardening design based on lightning alone will not be sufficient to guarantee EMP immunity. Similarly, consideration of EMP alone in the hardening design does not guarantee immunity from lightning.

V SYSTEM VULNERABILITIES

A. GENERAL.

Historically, the first lightning vulnerability modes to be considered involved structural damage caused by direct strikes. This problem was addressed by designing aircraft structures with sufficient electrical conductivity and mass to tolerate the anticipated direct effects. As the electrical and radio systems on aircraft became more complex, attention had to be paid to damage stemming from direct attachment to penetrations of the skin, such as aircraft antennas and lead-ins. Lightning arrestors for HF antennas were evolved, and shunt-fed antennas for VHF and UHF were developed to control the problem of conducting direct-strike currents to the interior. Receiver input circuits and transmitter output circuits were designed to tolerate the transients induced in the antenna systems.

Coupling of transient signals through apertures in the aircraft skin received attention in connection with problems of safety. It was necessary to insure that the voltages induced on wiring to electrical system (e.g., fuel-level gauges) inside the tanks in the wings were not sufficient to cause sparking and consequent fuel ignition.

Conventional flight-control systems involved direct mechanical linkages or hydraulics, both of which are unaffected by electrical transients. Communication and avionics systems used robust analog circuitry that was relatively unaffected by occasional transient pulses. Accordingly, relatively little attention was paid to the coupling through apertures of broadband transient signals.

With the introduction of modern, low-level, digital electronics into flight-critical systems, their vulnerability to broadband electrical transients was recognized as an important problem. Much work is currently under way in the aircraft community to devise ways of characterizing and controlling the problem.

B. SYSTEM VULNERABILITY THRESHOLDS.

1. General.

A threshold is defined here as the electromagnetic stress that produces a prescribed malfunction or unacceptable performance. The options available in choosing a threshold involve defining unacceptable performance, characterizing stress, and locating where in the system the stress shall be specified. Unacceptable performance is quite arbitrary and may vary from a detectable change in the mean time before failure (MTBF) to immediate damage to the system. As a practical matter, however, the threshold must be a quantity that can be determined or bounded in some way, and it must be amenable to specification and to control throughout the life of the system.

The threshold can be specified at any level in the system: at the terminals of a transistor, at the equipment terminals, or at the skin of an aircraft. However, the level in the system at which the threshold is specified affects the ability to design and test the EMP/lightning protection. Generally, thresholds deep in the system require knowledge about the EMP/lightning interaction with all the system exterior and interior structures between the specified surface and the source to determine the EMP/lightning-induced stress at that level. Thresholds specified at the outer levels of the system facilitate determination of the EMP/lightning-induced stress by eliminating the need to understand the complex circuit response for all of these states, provided the EMP/lightning-induced stress is not the dominant stress inside the surface at which the threshold is specified.

2. Threshold Choices.

If the EMP/lightning-induced stress exceeds the threshold stress, an unacceptable response will occur, or an unacceptable risk will exist. Some of the conditions that might be used to define unacceptable performance, as well as some of the peculiar traits of each condition are described below.

Damage. Systems must be protected at least against stresses that can cause unacceptable damage. However, component manufacturers usually specify and control normal and maximum safe operating levels. Damage levels are neither specified nor controlled; they tend to vary with manufacturer, lot, time of manufacture, and other specified parameters. Hence, it is not possible to predict accurately the damage threshold, and it is nearly impossible to measure the damage threshold without destroying the test article.

In addition, damage can occur in subtle ways. The damage threshold of a component is frequently assumed to be the EMP/lightning-induced energy that will damage the component. However, the EMP/lightning may merely trigger the release of much larger energies stored in the system or supplied to the system by its operating power source. Under these conditions, a trivial amount of energy can induce extensive system damage. Nondamaging EMP transients can drive digital circuits into unintended states in which they destroy themselves or become locked up so that, while not physically damaged, they are no longer useful.

Thus, while the protection must at least prevent damage to the system by the EMP/lightning, the stress that causes damage is usually difficult to define and control. In addition, using damage as a threshold usually implies understanding EMP- or lightning-induced effects deep in the system. Hence, when damage is used as a threshold, a large margin is usually used to account for these uncertainties.

Upset. Circuit upset usually implies a condition in which a digital circuit toggles unintentionally. The upset stress is usually specified and controlled for the operating waveform; for other waveforms, some accommodation must be made for difference in waveform, duration, etc. The characteristic of the transient that determines whether or not it causes upset is frequently its impulse value (the area under the pulse), but for oscillatory transients, other properties, such as frequency of oscillation, can be important. However, all of this applies only if the transient is impressed in the same way as the normal switching signal.

Upset thresholds are usually associated with digital circuits, or equipment containing such circuits, that are usually fairly deep in the system. Hence, the stress induced at this level in the system by an external source is usually difficult to determine accurately.

Operating Level. It is sometimes proposed that a more reliable, well-controlled threshold is the operating signal level. These properties appear to apply to excitation with the normal signaling modes and design waveforms. However, abnormal modes and out-of-specification waveforms that might be induced by the lightning or other external transients appear to require all of the special considerations noted above for abnormal modes. Hence, the upset and operating-level thresholds have similar characteristics.

System-Generated Stress. All systems generate transients and other spurious signals internally during normal operation. It has been postulated that if the externally induced transient is reduced until it is smaller than these system-generated transients, no further improvement in the protection is beneficial, since the internal system environment is then determined by the system, not the external lightning currents. Furthermore, since the internal equipment and cabling tolerate the system-generated stress routinely, they will not be adversely affected by the weaker lightning-induced stress, and no lightning-peculiar requirements on the interior of the system are required.

Although the system-generated transients can be defined at any level in the system, the most interesting level is just inside the system-level EMP barrier. If the protection is designed to make the system-generated transients the dominant stress at all points inside this barrier, one need not know how the lightning interacts with the internal circuits and equipment to know that they will tolerate lightning.

No Change in MTBF. If the lightning-induced stress is made so weak that it does not shorten the MTBF, then it has certainly been reduced sufficiently. While this is an interesting concept, it is not useful for designing lightning protection, because the MTBF is generally not a predictable quantity (except to the extent that historical data exist for components and processes used in the system), and the effect of the lightning-induced stress on MTBF is even less predictable. Furthermore, it is very difficult to test or otherwise evaluate the system's ability to meet the MTBF criteria.

C. ELECTROMAGNETIC SOURCE PROPERTIES AND THEIR IMPORTANCE IN VULNERABILITY CONSIDERATIONS.

1. General.

A unique aspect of EMP- and lightning-induced stresses is their transient nature. The interference control community is accustomed to specifying tolerances and interference as single-frequency or narrow-band fields or voltages for which an amplitude alone suffices as the magnitude of the stress. For transients, however, specifying a stress is much more complicated, since the system may respond to the rate of rise, the peak amplitude, the energy, or some other property of the transient signals induced in its circuits, as indicated earlier in this section. To further complicate matters, the waveform for which the system threshold is known is not necessarily the same as the waveform the EMP/lightning induces at that point in the system. Thus, in assessing the effects of EMP- and lightning-induced stresses on system operation, we may need to account for differences in waveforms as well as system sensitivities to different properties of the waveforms. Some characteristics of the source signals that appear significant here are discussed below.

2. Source Properties of Primary Importance.

Rate of Rise. Mutual coupling of the form Ldi/dt and Cdv/dt, and loop and dipole responses, dB/dt and dD/dt, depend on the rate of rise or rate of change of the waves. Consequently, system responses that depend on mutual coupling will depend on the first derivative, d/dt, of the driving waveform. In particular, a high rate of rise of the source waveform is required to induce currents in aircraft wiring.

Peak Value. The peak voltage or peak current is sometimes the critical factor in upset or inadvertent toggling of digital circuits. The peak voltage is also a primary factor in dielectric breakdown and in some junction breakdown phenomena. For a given waveform, (or a given spectral form) the peak value of the signal induced in wiring on the inside of the aircraft is proportional to the peak value of the illuminating signal.

3. Source Properties of Lesser Importance.

Impulse or Total Charge Transferred. This function is the integral of the voltage or current:

$$\text{IMPULSE} = \int_0^\infty V\,dt, \text{ or } \int_0^\infty I\,dt \quad .$$

This characteristic of the lightning source was of great interest to the aircraft lightning community when interest centered primarily on questions of physical damage to the metal structure of the aircraft. It is of relatively minor importance in determining currents induced in internal wiring.

Action Integral. This characteristic of the lightning flash defined by

$$\text{ACTION INTEGRAL} = \int i^2\, dt \quad ,$$

is also of primary interest in connection with damage consideration — particularly melting. It is of secondary importance in describing the effects on internal avionic systems.

D. SUMMARY.

In light of the discussion in Sections V-C-1 and -2 above, it appears that peak value and rate of rise of the source signal are of principal importance in determining effects on avionic systems. These two parameters translate into high-frequency energy content in the frequency domain. Thus, in comparing the electromagnetic properties of EMP and lightning, these are the parameters that must be applied to the comparison.

VI APPLICATIONS OF LIGHTNING TO EMP PROBLEMS

A. MOTIVATION

As indicated earlier, lightning and EMP both involve processes capable of generating high-amplitude transient electromagnetic signals. Accordingly, it is appropriate to investigate the similarities and differences in the two sources to determine the degree to which work in one area can be applied to the other.

First, one can observe that both lightning and EMP generate high-level electromagnetic signals. Whereas aircraft are exposed to lightning periodically in the normal course of their operation, they are never exposed to EMP. Thus, to assess aircraft EMP hardness, it is necessary to build high-level electromagnetic pulse sources to which aircraft may be exposed to determine the degree to which they meet appropriate EMP hardness specifications. Accordingly, there is strong motivation to look into the feasibility of using an aircraft's normal exposure to lightning as an assessment or "proof test" of its EMP hardness. This issue is discussed in Section VI-B.

Second, we start again from the observation that both lightning and EMP radiate high-level transient electromagnetic signals; unlike EMP, however, lightning impulses occur frequently in peacetime and are generated free of cost. Simulated EMP pulses, on the other hand, require substantial initial investment and involve considerable operating cost for their generation. Thus, it is appealing to consider the use of deliberate exposure to lightning as the transient electromagenetic source for EMP hardness and surveillance studies of aircraft. The concept of using deliberate exposure to lightning as a proof test is discussed in Section VI-C. The concept of using deliberate exposure to low-level lightning as a source for coupling studies is discussed in Section VI-D.

Third, since both lightning and EMP involve high-level transient processes it is appropriate to consider the feasibility and desirability of unifying the specification and testing of aircraft to survive these threats. This topic is discussed in Section VI-E.

Fourth, it has been suggested that the lightning simulation testing normally carried out during the development and certification of aircraft provides insight regarding EMP hardness. This topic is discussed in Section VI-F.

B. NORMAL LIGHTNING EXPOSURE AS A PROOF TEST OF EMP HARDNESS.

1. General.

If the normal exposure to lightning during aircraft operation is to be used as a "natural" EMP proof test, it is necessary that certain conditions be fulfilled:

- The characteristics of the electromagnetic signal radiated by lightning must be such as to stress the aircraft in the same way and to the same levels as would EMP. This implies that the time waveform (or spectrum) must be appropriate, and that the amplitude must be adequate.
- In the normal course of operation, the frequency of encounters of the aircraft with lightning must be adequate to ensure that it has indeed been adequately exposed to lightning of proper intensity.

To address these issues, it is necessary to consider the relevant electromagnetic characteristics of lightning and how they compare with EMP. Such a comparison is not straightforward because the EMP signal represents one major transient event, while a lightning flash generates a succession of ten thousand or more pulses. In discussing lightning, it is necessary to consider the principal experimental techniques that have been used in its study (primarily ground measurements), and the extent to which various data can be used to compare lightning and EMP. In this regard, it is important to note that aircraft and avionic system characteristics are such that the aircraft systems "see," one pulse at a time, the numerous pulses that make up the lightning discharge (i.e., the effects of one pulse have died out before the next one arrives). Thus, results of experiments designed to yield lightning data on a pulse-by-pulse basis are directly applicable. Other narrowband spectral-measurement techniques yield data that are difficult to use at best, and frequently are seriously misleading.

Statistical data on normal lightning exposure of aircraft are also important. This information must be considered because the amplitude of the lightning signal falls off rapidly with distance from the lightning current channel. Accordingly, it is necessary to estimate how frequently an aircraft can be expected to be sufficiently close to the lightning source to be excited to useful levels.

2. EMP Properties and Interaction With Aircraft Systems.

As discussed earlier in this report, the radiated field from the high-altitude nuclear EMP (HEMP) consists of one major transient event per burst. Since the pulse rise time may be 10 ns or less, the signal is rich in high-frequency energy. As a result of the large size of the near-planar source region, the radiated signal is a uniform plane wave covering an enormous geographical area. Thus, the HEMP interaction with an aircraft is unaffected by substantial changes (hundreds of kilometers or more) in aircraft location. It should be noted that HEMP interacts with aircraft entirely through the radiated field -- there is nothing corresponding to the lightning direct strike.

Plane wave EMP interacts with a system and produces transient currents and voltages on system conductors. The waveforms of these induced transients are usually represented as superimposed damped oscillations, with the ringing frequencies determined by the dimensions of system conductors and by their impedances. For example, the fuselage resonance of most aircraft is in the range 1 to 10 MHz, and many of the interior wiring resonsances are above 20 MHz. The amplitude of these induced transients depends on the source spectrum and the coupling transfer function relating the source to the response. In particular, it should be noted that if the source signal contains no energy above 20 MHz (and the system remains linear), there will be no internal response above 20 MHz.

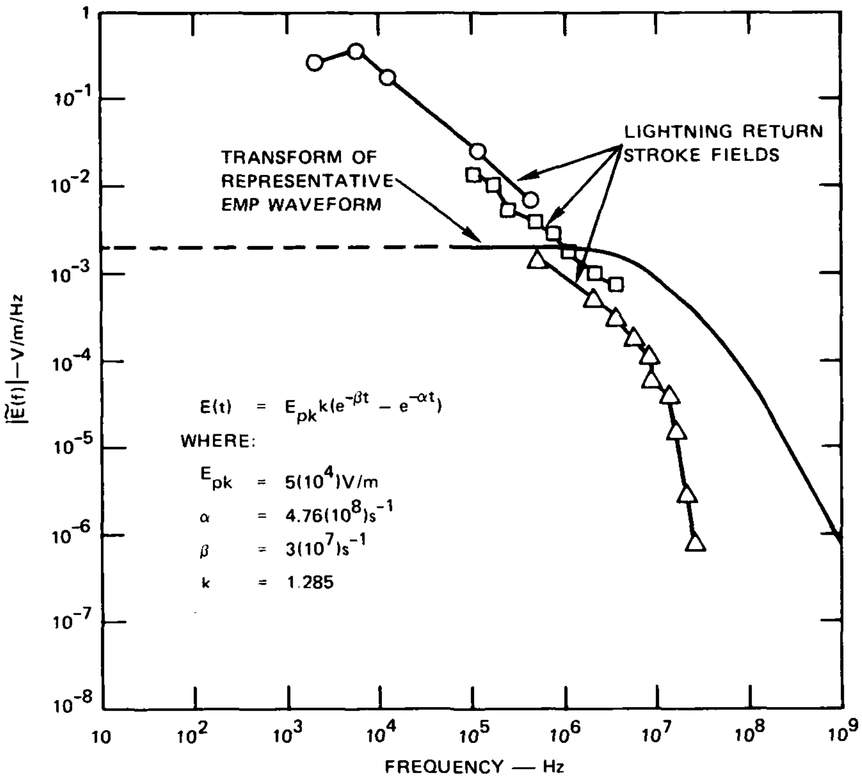
3. Lightning Properties.

As indicated in Section II-A, a lightning flash typically lasts 0.5 s and consists of a large number of diverse processes, each of which generates an electromagnetic signal. Lightning interacts with systems in two ways: by radiation of the fields associated with cloud processes and ground return strokes, and in addition, by direct attachment of stroke currents to system conductors. Radiation of fields from lightning strokes produces responses somewhat similar to those produced by EMP -- namely, damped sinusoidal oscillations at frequencies determined by the dimensions of system conductors. The peak amplitude of the induced current is a strong function of the energy in the source at the frequencies of interest -- to above approximately 20 MHz for most aircraft as noted earlier. Since the lightning channel is a line source, the field intensity decreases rapidly with increasing distance from the channel.

In comparing the effects of lightning and EMP, it is important to consider their source spectra. Figure 21 shows a comparison of the electric fields from a representative EMP Waveform and from the lightning ground-return stroke -- the most energetic process in a lightning flash. The lightning data are return stroke data from Figure 19[32] and have been multiplied by 1000 to scale the fields inward from 50 km to 50 m from the stroke. (Scaling is necessary because the lightning field decays rapidly with distance for the channel. The distance of 50 m is arbitrarily chosen as representing the closest distance a lightning channel can approach an aircraft without diverting to the aircraft.)

The radiated lightning environment is more severe than EMP below 1 MHz, and the EMP environment is more severe in the important region above 1 MHz where the aircraft responses occur. The lightning data are averaged in Reference 32; the rare severe lightning may be five times larger than the values shown. It is important to note that the lightning spectral data in Figure 21 were generated by taking FFTs of single lightning-impulse time waveforms.

It will be recalled that, in connection with the discussion of Figure 7 in Section II and Figure 13 in Section III, it was concluded that spectral data generated by FFT of the broadband signatures of individual lightning events were most appropriate for the investigation of lightning effects on aircraft avionic systems.



NOTE: Representative EMP Waveform Is Limited In Its Applicability To Early Times ($t \lesssim 1$ μs) And to High Frequencies ($t \gtrsim 10^5$ Hz)

SOURCE: DOD Instruction 5210.58 (rev.), Electromagnetic Pulse (EMP) Security Classification Guide (U), contract DNA 001-81-C-0209 (April 1984)(Secret RD; in publication)

FIGURE 21 COMPARISON OF LIGHTNING AND EMP SPECTRA

Narrowband spectral measurements made on the ground tend to include the effects of the thousands of VHF sources distributed throughout the interior of the storm cell as shown in Figure 2, whereas an aircraft flying in the storm cell can be near only a few of these. Furthermore, the pulse "stacking" that occurs in connection with narrowband measurements of lightning spectra tends to contaminate the data for use in the study of aircraft systems. In other words, the narrowband data include many small pulses that occur in a flash and add to the total energy radiated at VHF. For our purposes however, we do not care how many pulses occur -- we are interested in looking separately at the processes that take place within a few microseconds of each pulse. Attempting to do this using the narrowband data is complicated. First, we must somehow ferret out the measurement system characteristics and take them into account, along with the pulse repetition frequency of the lightning being studied.

4. Lightning Strike Statistics.

If a nearby lightning strike provided useful data on EMP hardness, the frequency of such events then becomes important. As indicated by a number of workers,[10,32] lightning is a highly variable process. When an aircraft is struck by lightning or flies near a lightning channel, it is not possible to know the characteristics of the flash of interest without careful and elaborate measurements. If lightning is to be useful for testing EMP hardness, we must be sure that sufficient exposures occur during normal operation to provide assurance statistically that lightning levels of interest will be experienced occasionally.

In this regard, the results of studies of relevant aircraft lightning encounters are summarized in Appendix C. Figure C-6 indicates that Air Force aircraft experience, on the average, one strike per 40,000 flight hours. Weinstock[57,58] indicates that Navy aircraft generally are struck once every 36,000 to 110,00 flight hours, in general agreement with Figure C-6. However, Weinstock observes that Navy fighter/attack aircraft are struck only once every 77,000 to 169,000 hours.

Let us consider a fighter aircraft and assume an average lightning stroke rate of once per 100,000 flight hours. If the aircraft is operated 1000 hours per year (roughly one-third the utilization of modern commercial aircraft, and probably high for fighters), the aircraft will be struck on the average once per 100 years. If we have a fleet of 500 such aircraft, we will observe 5 strokes per year to the fleet. For large rates of rise, we may be interested only in severe strokes of 140 kA or more in amplitude; Figure 4, Section II, indicates that these occur 2% of the time. Thus, such a strike will occur to our fleet only once every ten years.

In the earlier discussions of lightning effects, we did not consider direct strikes, but noted that high-current lightning within 50 m of the aircraft might be of interest. If such lightning is twice as likely as the direct strikes,* the 500-aircraft fleet would experience a high-level nearby strike once every five years.

Such exposure is hardly adequate to inspire confidence in the hardness of an aircraft type when we are interested in a scenario in which essentially all of the aircraft of a given type would be exposed to EMP at, for practical purposes, the same time.

*In actuality, such an assumption may overstate the frequency of nearby (within 50 m) lightning. Recent UHF radar observations of the NASA F-106 lightning research aircraft during its lightning-strike testing indicate that, most of the time, the lightning channel appeared to originate at the aircraft as if the aircraft triggered the stroke. Thus, the aircraft did not "fly into" the path of a propagating stroke.

5. Summary.

The electromagnetic signal generated by EMP is characterized by a rise time in the nanosecond regime. This means that the EMP signal is rich in HF and VHF energy and is very effective in exciting the external (few megahertz) and internal (tens of megahertz) resonances in aircraft. Since the EMP uniformly illuminates a large geographical area, substantial (hundreds of kilometers) changes in aircraft location do not affect EMP interaction.

Although the kilometers-long cloud-to-ground lightning produces dramatic and highly energetic electrical discharges, their time structure of the discharges is such that the electromagnetic energy they radiate is principally at low frequencies. Other more numerous, less dramatic processes in the lightning flash -- associated with meters-long channels -- generate pulses relatively higher in HF and VHF energy. However, when the various measurements are properly unscrambled, it appears that these individual short processes are no more energetic at HF and VHF than is the ground-return stroke.

Since the lightning channel is a line source of electromagnetic radiation, the field intensity decreases rapidly with increasing distances from the channel. To produce signals at all comparable to those produced by EMP in the frequency range of interest (HF and VHF) the lightning channel must be within at least 50 m of the aircraft.

Air Force and Navy lightning strike statistics can be interpreted to indicate that in a fleet of 500 fighters such exposure would occur once every five years. It is concluded that such an exposure rate is entirely inadequate to provide insight into the fleet's EMP hardness.

C. DELIBERATE LIGHTNING EXPOSURE AS A PROOF TEST OF EMP HARDNESS.

1. General.

To use natural lightning as the driving source in EMP hardness proof tests, it is necessary that, as a minimum, the following requirements be fulfilled:

- The characterstics of the electromagnetic field illuminating the aircraft must be clearly defined.
- Sufficiently high field intensities must be achieved to stress the systems to levels comparable to EMP.
- Adequate instrumentation must be carried to define the lightning-induced stresses and aircraft system response.

The consequences of these requirements are discussed here in light of their implications on aircraft instrumentation, ground instrumentation, test conduct, and overall complexity and cost.

Although simply exposing an aircraft to lightning sounds straightforward and uncomplicated, doing it in such a way as to yield useful, unambiguous data at acceptable cost is difficult. To gain maximum insight regarding system behavior, most EMP proof testing currently is done as near to threat level as simulator technology permits. Thus, the aircraft would have to be operated in parts of the thunderstorm cell where adequate signal level existed. Instrumentation and recording systems of the same general sort as those presently used in EMP simulation testing would have to be used to monitor the environment and the pulses induced in system circuitry and to indicate system behavior. The inherent variability of lightning and our inability to trigger it when and where we want it adds greatly to the complication of the test.

2. Lightning Source Characteristic Definition.

Defining the source illuminating the aircraft is not a trivial matter in high-level testing, since one is constrained to operate very near to the lightning channel to be assured of adequate signal strength. Attempting to use ground measurements to define lightning conditions, including such parameters as channel orientation in the vicinity of the aircraft, is inherently difficult. In addition, precise time correlation between the ground and airborne recording sytems is necessary. Elaborate measurement techniques, including the use of a one-of-a-kind ground-based UHF radar to locate the lightning channel, are being used by modern experimenters in efforts to properly characterize lightning in the vicinity of test aircraft.

Recent flight experiments have used a multiplicity of sensors on the skin of the aircraft to characterize the aircraft excitation.[44,45,49,50] Sensors decoupled from the airframe are currently being developed to characterize the propagating signal with as little as possible contamination resulting from aircraft responses.

In general, the problem of close-in lightning-source characterization is proving to be far from trivial to modern aircraft lightning experimenters.

3. Source Location.

To relate the lightning excitation of an aircraft to that produced by EMP, it is necessary to know the location of the source with respect to the aircraft and, if possible, to define the channel orientation. Some experimenters have used VLF lightning locators on the aircraft or on the ground to determine the location on the ground return stroke associated with the flash.[50] Further refinement is possible using a ground-based UHF radar to detect the scattering from the channel itself.[59] The short processes associated with the UHF radiation from precursor activity can be located using ground-based time-of-arrival,[23,24] or interferometric location systems.[60] However, the UHF sources may not be collocated with the return stroke.

Carrying the location system on the aircraft usually implies substantial weight or performance penalties. If the measurements are made on the ground, it is necessary to provide accurate timing and recording capability, both on the ground and on the aircraft.

4. Instrumentation Considerations.

In addition to the instrumentation discussed above to define the lightning environment, the test aircraft must carry the normal variety and complement of instruments used in ground-based simulator tests. These include current and voltage probes and high-speed oscilloscopes.

Since lightning occurs at random times, the oscilloscopes and other recording devices must trigger on the received signal. They cannot be fired by a trigger pulse as is often possible in ground testing. Triggering on lightning is further complicated by the fact that the system may be triggered by a portion of the lightning event that is inappropriate for EMP testing.

Ground tests can be performed on a large aircraft with much of the instrumentation located inside the aircraft skin. For testing fighter-type aircraft, available space is inadequate to house the required instrumentation. Accordingly, in ground tests, fiber-optic systems are used to carry measurement signals to recorders located away from the aircraft. Such an approach is very difficult in flight, because a set of extremely broad-band (hundreds of megahertz) telemetry systems would be required to replace the fiber-optic systems.

A further complication in performing in-flight testing is that the aircraft must be maintained in flightworthy condition. Thus, sensors, mountings, instruments, etc., must be carefully planned and submitted for airworthiness review and certification, all at very substantial expense. The sort of relocation of sensors and instrumentation typical of an interactive measurement program on the ground is virtually impossible on a flight test program.

Some perspectives on the magnitude of the overall instrumentation problem can be obtained from a review of the NASA F-106 lightning tests program currently being conducted by Pitts.[44] For five years, he has been flight testing and evolving an instrumentation system to enable him to define the electromagnetic environment on the exterior of his test aircraft. Weight and volume limitations, together with the complexity of the lightning signal, make this a formidable undertaking. Since Pitts' primary objective is the definition of the airborne lightning environment, he has not made any particular effort to measure signals on the interior of his aircraft. Thus, the airborne EMP experimenter would be faced with obstacles even more formidable than Pitts in his F-106 program.

5. Test Conduct.

A major encumbrance to testing with lightning as a source is that the lightning flash is a momentary event occurring at a random time with a random amplitude. Especially in flight, but also on the ground, the ability to capture a transient with an amplitude somewhere within a 40 dB range with a self-triggered recording system, in the presence of system-generated noise, is extremely difficult.

In current EMP test programs using transient simulators, a few shots are used to set up oscilloscope (or other recorder) gains, sweep speeds, and trigger time delays. Then one to a few shots are used to record data (a few repeats are often necessary because of pre-triggers, lack of trigger pulse, failure to arm, or any of a number of other equipment or personnel shortcomings). In these programs, trigger pulses are provided by sophisticated timing and firing systems that control the time of the test pulse and the time of arrival of the trigger pulse within a few nanoseconds. Such procedures are not possible when one is attempting to study the effects of very infrequent, close-in, high-level lightning.

In general, experienced testers insist on controlling the source, as well as the test object, whenever possible, because of the inefficiency and the hazard of not capturing the data if the source is not controlled. Even lightning effects testing is rarely done with natural lightning; artificial lightning sources are used to avoid these problems.

6. Summary.

The fact that lightning discharges are generated free of cost is very appealing. Unfortunately, the extreme variability and unpredictability of lightning make it difficult to use for this purpose. To obtain meaningful results, it is necessary to characterize the lightning signal illuminating the test aircraft and to define the aircraft system responses. The instrumentation system required to do this is more elaborate than the most modern systems flown in recent airborne lightning studies. Reliance on the random occurrence of lightning precludes the normal "setup shots" used in simulator testing to make sure that the measurement system is properly set to record good data. Thus, the rate at which useful data can be generated will be low.

To achieve an adequate signal level for proof testing, it would be necessary to operate within the storm cell -- in regimes of substantial turbulence -- presently entered deliberately only by lightning experimenters with specially hardened and fuel-inerted aircraft. In essence, such proof testing is not as simple, straightforward, and inexpensive as might be expected at first glance. Even lightning effects testing is rarely done with natural lightning; artificial lightning sources are used to avoid these problems.

D. DELIBERATE EXPOSURE TO LOW-LEVEL LIGHTNING TRANSIENTS FOR COUPLING-DETERMINATION TESTS

1. General

To use the lightning signals generated in the immediate vicinity of a thunderstorm cell to conduct low-level coupling-determination tests on an aircraft operation near the cell, it is necessary that the following requirements be met:

- The characteristics of the electromagnetic field at the location of the aircraft must be defined, and sufficient energy at the frequencies of interest must exist.
- Adequate signal levels must exist to overcome internally-generated noise; most aircraft systems must be turned on for the aircraft to fly.
- Appropriate instrumentation must be carried to define aircraft responses.

The implications of these requirements are discussed in terms of the various systems and elements involved in such a test. Substantial use is made of comparisons to the previous section discussing deliberate lightning exposure for proof testing. Source characterization is somewhat simpler because the lightning channel need not be near the aircraft. Signal level requirements are different than for proof testing, but they must be carefully considered because it is likely that an aircraft operated outside the cell may experience marginal signal levels. Elimination of the requirement for thunderstorm cell penetration eases the load on the pilot. As in the case of the proof tests discussed in the previous section, instrumentation and recording systems of the same general sort as those presently used in EMP simulation testing would have to be provided in the aircraft to monitor the pulses induced in system wiring.

2. Source Characteristics.

Defining the source illuminating the aircraft must be carefully considered. For the low-level tests being discussed, one might consider flying the aircraft in the vicinity of the cell and using the signals generated by ground strokes as the driving signal source. Ground strokes can be located reliably using modern ground-based measurement techniques, and their electromagnetic properties at the ground can be well defined provided the stroke channel is far enough away. To check the validity of the ground measurements, it would be prudent to equip the aircraft with a limited number of sensors on the skin to characterize its excitation.[44,45,49,50]

3. Source Locations.

Since the radiation from ground strokes would be relied on for the source of low-level exitation, the location of the source could be determined using a low-frequency lightning location system.* Since properly designed low-frequency location sytems operate on the leading edge of the ground return-stroke pulse, the orientation of the channel at the time of detection and location is also defined (largely vertical).

4. Instrumentation Considerations.

In addition to a few sensors with associated instrumentation discussed above to define the lightning environment, the test aircraft must carry the normal variety and complement of instruments used in ground-based simulator tests. These include current and voltage probes and high-speed oscilloscopes. As discussed in the previous section on proof testing with the lightning source, triggering must be done on the received signal with the attendant possibility that the system is triggered on an uninteresting or inappropriate portion of the lightning event. Provisions must be made to indicate where, on the overall lightning waveform, the high-speed recording systems are triggered.

The requisite sensors and instrumentation must be designed to fit in the test aircraft, which must be maintained in flightworthy condition. On a large aircraft this generally is not a major problem. On fighters, however, designing and assembling an appropriate instru-mentation system can be very time-consuming and costly. A further problem on small aircraft is that with the complete instrumentation system on board and certified flightworthy, the internal configuration would be so altered that the credibility of the test would be suspect.

5. Test Conduct.

Testing with a randomly occurring, complex, low-level source in the presence of system-generated noise is challenging. (Since the aircraft is in flight, many systems cannot be turned off.) On a hardened aircraft, internal responses to threat stresses should be comparable to the level of transient activity generated on-board by system operation (power switching, rectification, etc.). For the lower excitation by remote lightning, it is doubtful that the internal responses could be detected in the presence of this on-board activity. Experience with power-on testing under simulated EMP excitation has demonstrated that even with excellent timing and firing control, it is difficult to discri-

*For example, location systems developed by Uman and Krider, Lightning Location and Protection, Inc.

minate between the induced response and the on-board "noise." As with all testing with random signals, many shots will be wasted for one reason or another. In addition, since ground measurements will be needed for source characterization, any problem with the ground system or with time synchronization can invalidate otherwise useful airborne data. All in all, the overall data rate in such a measurement program is likely to be quite low.

In general, unless the ground-based low-level simulators are not available, one would be well served to consider their use before embarking on the major effort required to instrument an aircraft to yield useful data from low-level lightning transients. (We again note that even lightning testing is now done largely with ground-based simulators to increase the data rate and control and reduce the cost of such testing.)

6. Summary.

In attempting to use deliberate exposure to low-level radiated lightning signals as the source for EMP coupling tests, one is faced with the same general instrumentation problems that were identified for deliberate high-level proof testing. In the present case, however, since the aircraft need not be operating in the immediate vicinity of the lightning channel, much of the source characterization and location might be done from the ground so that the aircraft instrumentation system will be simplified slightly -- the instrumentation needed to characterize the signals induced on the interior of the aircraft would be unchanged. Also, since the aircraft need not deliberately penetrate the storm cell, some of the special considerations associated with such operations would be eliminated. The data system would still be quite complex, and since the aircraft must be kept in flightworthy condition, configuration changes that evolved as the program progressed would be time-consuming to implement. The need for careful time synchronization with the ground adds complexity to the system. Relying on a ground system for part of the data also restricts the freedom of the aircraft to search for appropriate storm cells.

Acquisition of data using a random source entirely out of the control of the experimenter is time-consuming, because there are few strokes available and many of these are sure to be wasted. The problem is particularly complicated in the case of lightning, because a single flash is composed of a large number of electromagnetic processes, a few of which are of interest, but many of which are capable of triggering the data acquisition system. In general, implementation of such a test would be costly, and the data output would likely be limited.

In essence, it must be observed that flight testing is appropriate for (1) gathering basic data not available in any other way, and (2) proving a design or other concept. Flight testing is not appropriate as a substitute for low-level ground-based experiments.

E. LIGHTNING RESEARCH AND EMP SPECIFICATION UNIFICATION

1. General.

Periodically, it is suggested that the EMP community should make greater effort to take advantage of ongoing and projected work directed at further clarifying the electromagnetic properties of lightning, particularly at high frequencies, with a view toward applying the results to EMP problems. These suggestions also frequently indicate a need to pursue and support activities directed toward the unification of all electromagnetic tests and specifications.

The essence of these suggestions was appreciated independently by DNA and AFWL, and programs addressing these areas have been under way for some time.[61-63] The background of the motiviations are outlined here together with an indication of the direction in which current activity is proceeding.

2. Technical Discussion.

Present lightning tests and specifications for aircraft were developed in an effort to ensure that the aircraft would tolerate the physical damage produced by a direct attachment of lightning ("direct effect"). Of principal concern in this regard is the duplication of the peak current, total charge transfer, and action integral of the stroke. Thus, there is little commonality between lightning and EMP in this respect.

Recently, the aircraft lightning community has become more concerned with the effect of lightning transients on avionic systems in the interior of the aircraft ("indirect effects"). This interest is largely the result of the recognition that modern digital avionic systems can be disabled by electromagnetic transients. Of interest in this regard are the rate of rise of the lightning signal and high-frequency processes in general. These are the same parameters of interest in EMP hardening.

Recent work in the area of atmospheric electricity indicates that various processes in the overall lightning flash are capable of generating fast-rising transient signals. Thus, lightning simulators must be designed with careful attention to the generation and application to the test aircraft of high-amplitude, fast-rising electromagnetic transients. Many of the pulse generation and measurement techniques developed in connection with EMP studies are now being applied to lightning work.[64-66] Many of the high-frequency techniques evolved for EMP testing are being used in lightning tests. Further efforts to unify lightning and EMP testing and specification certainly appear to be worthwhile and are being addressed by DNA and AFWL in their current programs.

3. Summary.

Both of the above suggestions involve efforts to better integrate the EMP community with related activities in other areas. There has already been a substantial transfer of high-frequency measurement and simulation technology from the EMP community to the area of aircraft lightning test and simulation. Active programs are under way by DNA and AFWL to maintain contact with and provide modest support to selected workers in the area of atmospheric electricity to make certain that the EMP community is apprised of new developments. The idea of pursuing lightning research to define significant new properties relevant to EMP considerations is certainly of interest. In particular, efforts to develop fuller understanding of lightning processes -- particularly those responsible for VHF signal generation — should be encouraged and supported. Specifically, measurements to unify VHF time-domain, frequency-domain, and source-location measurements are badly needed. Continued activity by the EMP community to maintain awareness of current lightning work is very important -- particularly since there appears to be much relevant work in the offing.

The program of unifying all system electromagnetic specifications undertaken by DNA should continue and include modern insights regarding lightning. It is particularly important to develop an appreciation of the differences between intrasystem electromagnetic compatibility (EMC) and protection of the entire system against external sources such as lightning and EMP. In addition, the implications of validating and maintaining protection against a threat that the system never experiences in peacetime must be understood and accounted for in the standardization of EMP hardening.

F. LIGHTNING TESTING DURING AIRCRAFT DEVELOPMENT AS AN ASSURANCE OF EMP HARDNESS.

Occasionally it has been suggested that the lightning simulation testing normally accomplished during the development and certification of an aircraft is adequate to ensure its EMP hardness. Unfortunately, the lightning testing carried out during the development of the aircraft in the current inventory has not ensured their lightning immunity as is indicated in Appendix C, which summarizes the accident studies of References 67 to 75. The scope of the problem for the USAF is succinctly summarized in the following, which is extracted verbatim from Reference 68 and which reflects USAF statistics as of February 1979:

> "More than half of all Air Force weather-related aircraft mishaps are caused by lightning strikes. The USAF financial loss incurred in such mishaps ex-ceeds 21 million dollars in the past five years, besides two aircraft lost with eight lives in 1978 alone. In the past ten years, seven USAF aircraft losses have been confirmed as lightning-related, two others ascribed to lightning as a likely cause, and over 150 serious mishaps reported. Imputed mechanisms include pilot disorientation and instrument failure (F-101, F-106), flight control failure after high-current penetration (F-111F), fuel tank explosion, dual

engine flameouts with electrical failure (F-4), fuel tank burn-through and explosion (C-130E), and failure of unprotected nonmetallic rotor blades (HH-33). A probable lightning-associated fuel ignition caused the loss of an Imperial Iranian Air Force 747 aircraft on 9 May 1976 near Madrid, Spain."

In Reference 72, Corbin has reviewed Air Force lightning mishap reports covering the period 1970-1982. Data from Reference 72 on the interference/outages attibuted to lightning strikes are shown in Figure C-5 (Appendix C). A breakdown showing the systems affected is shown in Figure C-5a. Navigation systems and flight instrumentations are the most vulnerable overall.

Figure C-5b indicates that small aircraft typified by fighters and trainers are more vulnerable to lightning than larger aircraft such as bombers and cargo aircraft.

Figure C-5c indicates that the system affected most strongly depends on the aircraft type. Flight instrumentation and navigation were most affected in fighters, while navigation was predominantly affected in cargo aircraft. These differences can in part be explained in terms of lightning attachments to the pitot system and air data sensors on fighter aircraft (which impacts flight instrumentation indicators) and a high percentage of attachments to the nose radome on cargo aircraft (which impacts weather/navigation radar). Engines were affected in fighters and trainers, but were not a factor in cargo aircraft.

In light of the above military experience with lightning, it is evident that the lightning simulation tests applied during the development of the current inventory of aircraft did not ensure lightning hardness. Accordingly, it would be imprudent to assume that these simulation tests were adequate to ensure EMP hardness.

VII CONCLUSIONS AND RECOMMENDATIONS

The principal objectives of this program were to investigate physical and electromagnetic properties of lightning and to compare and contrast them with EMP. Several motivations existed for this work. First was the attractive possibility that exposure to lightning during normal flight operation resulted in sufficient electromagnetic stress of avionic systems to constitute an EMP hardness verification or surveillance. Second was the possibility of using lightning signals as an inexpensive source of high-level electromagnetic transients for the conduct of EMP testing. The third was the desirability of unifying lightning and EMP tests and specifications.

Although lightning and EMP both generate high-level electromagnetic transients, there are important differences in their basic source mechanisms that greatly complicate efforts at comparing the two sources or using the effects of one to study system response to the other. Each high-altitude nuclear event generates a short high-amplitude electromagnetic transient that covers a large geographical area and propagates as a plane wave. Thus, any system within this area is illuminated by the pulse.

A lightning flash, on the other hand, is composed of a large number of diverse electrical discharge processes occurring for a period of about 0.5 s. The current channels associated with these discharge processes range in length from a few kilometers to a few meters. The long channels are responsible for the radiation of low-frequency signals, while the short channels are the sources of much of the VHF radiation associated with the flash. The flash consists of hundreds or thousands of small pulses and a few medium-to-large return strokes. The amplitudes, waveshapes, and relative positions of the sources for these transients are not predictable, although some general characteristics have been ascribed to the average properties of the larger transients. The amplitude of the radiated signal falls off rapidly with distance from the lightning channel.

The return stroke has received the most attention from lightning researchers, because this is the portion responsible for the damage generally associated with a direct strike. Hence, substantial information exists about the average and extreme properties of return strokes. However, lightning interaction with interior circuits in systems appears to be dominated by the large rates of change associated with the leading edge of the return stroke and with the many smaller precursor pulses. Until recently, little attention had been given to these parts of the lightning event, and their properties are still not established. Nevertheless, there is a growing body of evidence suggesting that the precursor pulses originate at diverse locations throughout the volume of the thunderstorm system and are not directly associated with the return stroke.

Comparisons of lightning and EMP spectral energy in the frequency regimes of interest in affecting avionic systems (HF and above) indicate that the lightning source must be very near the aircraft before it produces effects comparable to EMP. Lightning strike statistics suggest that such close encounters (within 50 m of the aircraft) occur very infrequently. Thus, in light of the great uncertainty regarding the levels and characteristics of the lightning transients to which an aircraft is exposed during normal flight operation and the frequency with which an aircraft is exposed, it would be very imprudent to use such exposure as the basis of an assessment of EMP hardness without instrumentation to measure and quantify the lightning exposure.

In attempting to use lightning radiation as the electromagnetic source for EMP simulation, one is faced with the need for carrying elaborate sensors and instrumentation to characterize the transient pulses with which the aircraft has been illuminated. (This instrumentation would have to be similar to that currently employed by airborne lightning experimenters in their programs to characterize lightning strokes to aircraft.) Additional airborne or ground-based instrumentation must be provided to define the location of the lightning current channel with respect to the aircraft.

To achieve signal levels approaching threat level (as is currently done in EMP testing to require the least possible extrapolation) it would be necessary to operate the aircraft within the thunderstorm cell to be near the lightning stroke channels. The instrumentation used to define system responses and excitations within the aircraft would have to be similar to that presently used in ground-based EMP testing.

Finally, the need for designing the instrumentation system to work on random transient signals occurring at uncontrolled times poses an additional challenge. Consequently, it is concluded that efforts to use natural lightning to conduct EMP tests would be very expensive and would require substantial flight time and risk to the aircraft and crew if they were to yield data of the sort currently being generated in simulation tests.

Further efforts to unify lightning and EMP testing and specification certainly appear to be worthwhile. Many of the high-frequency techniques evolved for EMP testing are being used in lightning tests. The program of unifying electromagnetic specifications undertaken by DNA should continue and include modern insights regarding lightning.

Efforts to develop fuller understanding of lightning processes — particularly those responsible for VHF signal generation -- should be encouraged and supported. In particular, measurements to unify VHF time-domain, frequency-domain, and source-location measurements are badly needed.

Continued activity by the EMP community to maintain awareness of current lightning work is very important, particularly since there is much relevant work in the offing. (Many of the planned lightning programs are summarized in Appendix D.)

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Appendix A

SUBCONTRACT TO LIGHTNING LOCATION AND PROTECTION, INC.

In support of the activities on this program, a subcontract was issued to Lightning Location and Protection, Inc. (LLP), of Tucson, Arizona, to enable Drs. M. A. Uman and E. P. Krider to make additional data analyses and analytical calculations of interest in the comparisons of lightning and EMP. The data of Weidman[29] were used to investigate the correlation between dE/dt and ΔE for return strokes. This information is of interest in connection with the scaling of rise-time data to different lightning current levels.

They also carried out analytical calculations investigating the effect of channel tortuosity in increasing the spectral amplitude of lightning above 10^5 Hz. Their results indicate that the effect should be far less pronounced than predicted by Levine and Menenghini.[76] They hope that tortuosity measurements currently under way at the University of Arizona will help resolve this apparent contradiction.

Part of the funding was used by LLP to review and refine the calculations carried out in preparing a paper entitled "A Comparison of Lightning Electromagnetic Fields with the Nuclear Electromagnetic Pulse in the Frequency Range 10^4 to 10^7 Hz," which had been accepted and was under final review and revision for publication in the IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-24, No. 4, pp 410-416, November 1982. An error in one of the fast Fourier transform (FFT) codes used in the calculations was discovered and corrected.

The Final Report submitted by LLP makes up the remainder of this appendix.

LIGHTNING AND THE NEMP

November 19, 1982

FINAL REPORT
SUBCONTRACT NUMBER: C-10681

to

SRI International
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Deputy Director
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by

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Introduction

In this final report, we compare the time-domain fields and frequency spectra of lightning return strokes and the NEMP, and we discuss the uncertainties both in the measurements and in the calculations. The basis for much of the discussion is contained in a paper we have written for the IEEE Transactions on EMC and which is scheduled for publication in November 1982. This paper is reproduced in the Appendix, and it should be noted that funding from SRI International partially supported this work. In addition to the lightning-NEMP comparison, we will also give the results of some initial calculations on the effects of lightning channel tortuosity on the time-domain fields and some additional high frequency spectra of return strokes.

Lightning and NEMP

The NEMP field waveform we compare with lightning and its frequency spectrum are found in the Appendix. This is the preferred NEMP waveform among NEMP researchers, at least in the unclassified literature.

Lightning return stroke fields are computed from currents that have been obtained in two ways: (1) from direct measurements on instrumented towers that have been struck by lightning and (2) by inferences of currents based on EM field signatures that have been measured remotely. The best available direct current measurements are discussed in the Appendix. Most of the data come from Berger and Garbagnati and are based on strikes to towers on two mountains near the Swiss-Italian border. In these data, the risetimes of first return strokes are considerably slower than those of subsequent strokes and a peak current derivative, $^{dI}/dt$, of 1×10^{11} A/s occurs in about 1% of the subsequent strokes.

In a South African study, a $^{dI}/dt$ of 1.8×10^{11} A/s was measured for one lightning strike to a tower on relatively flat ground in a small sample of flashes. This case is apparently the largest $^{dI}/dt$ that has been measured directly. Whether currents measured on towers are truly representative of the currents in the lightning channel above ground, or of the currents that would flow through an aircraft above ground, is not known. The shape of the tower current, particularly that of the first return stroke in a flash, is not consistent with the electric and magnetic fields produced by normal lightning to ground (Weidman and Krider, 1978). Unfortunately, there are no simultaneous measurements of the EM fields and currents during natural lightning strikes to towers. The French (Fieux et al., 1978; Djebari et al., 1981) have measured currents and close fields during subsequent strokes in rocket-triggered flashes, and they have used these measurements to compute return stroke velocities using the theory given in the Appendix. Using this method, the French obtained a mean velocity of 1.3×10^8 m/s with a standard deviation of $.34 \times 10^8$ m/s using magnetic fields, and a mean of 1.7×10^8 m/s with a standard deviation of $.43 \times 10^8$ m/s using electric fields (Fieux et al., 1978; Djebari et al., 1981). Both of these means are consistent with the photographic measurements of Idone and Orville (1982) who report a mean of 0.96×10^8 m/s for first strokes within 1 km of ground and 1.2×10^8 m/s for subsequent strokes. Therefore, we regard the French measurements on triggered lightning as providing some support for the theory given in the Appendix. It is interesting to note that the 10-90% risetime of the French current pulse that is shown as an example is about 0.1 μs and that the peak current is about 10 kA (Fieux et al., 1978).

Return stroke currents that are derived from measured fields have a mean maximum $^{dI}/dt$ of about 1.5×10^{11} A/s, and the maximum measured value is about 4×10^{11} A/s in about 100 measurements. Therefore, the mean maximum $^{dI}/dt$ derived from fields is equivalent to the 1% level in the tower data. In the Appendix, we have assumed that a typical lightning has maximum $^{dI}/dt$ of 1.5×10^{11} A/s and peak current of 35 kA, and that a severe lightning has a maximum $^{dI}/dt$ and peak current that are 5 times those of the typical lightning, i.e. 7.5×10^{11} A/s and 175 kA, respectively. These choices for a severe lightning have been criticized because they associate the largest peak current with the greatest $^{dI}/dt$. We shall explore the validity of these choices below.

Fig. 1 shows the submicrosecond structure of a typical return stroke radiation field, and identifies the portion just prior to the peak that has the largest $^{dE}/dt$. In our model, $^{dE}/dt$ is directly proportional to $^{dI}/dt$ and the constant of proportionality contains the return stroke velocity near ground, as noted in the Appendix. A histogram of measured $^{dE}/dt$ values normalized to 100 km for the fast field transition are plotted in Fig. 1 for lightning at a number of distances over salt water (Weidman and Krider, 1980; Weidman, 1982). These measurements were made over salt water, and evidently the propagation distance does not affect the measured values. The mean maximum $^{dE}/dt$ during the fast transition is 33 V/m/μsec normalized to 100 km, and the mean 10 to 90% field risetime is 90 nsec during the fast transition.

Fig. 2 shows the relationship between the maximum $^{dE}/dt$ and the corresponding ΔE during the fast transition. The values of $^{dE}/dt$ and ΔE do appear to be correlated, and this implies that a large current peak will produce a large $^{dI}/dt$ as we have assumed for our severe lightning. On the other hand, only 8 out of 108 points in Fig. 2 are above 50 V/m/μs, and these have a larger variation in ΔE than the points below 50 V/m/μsec. Therefore, it might be argued that there is not enough $^{dE}/dt$ data to draw a firm conclusion about the distribution at high values of $^{dE}/dt$. It has been suggested that the data may be approaching a limit at about 75 V/m/μs, but this does not appear to be valid in view of the small number of measurements. It has also been suggested that the data above 50 V/m/μs may be produced by a different process than the data below

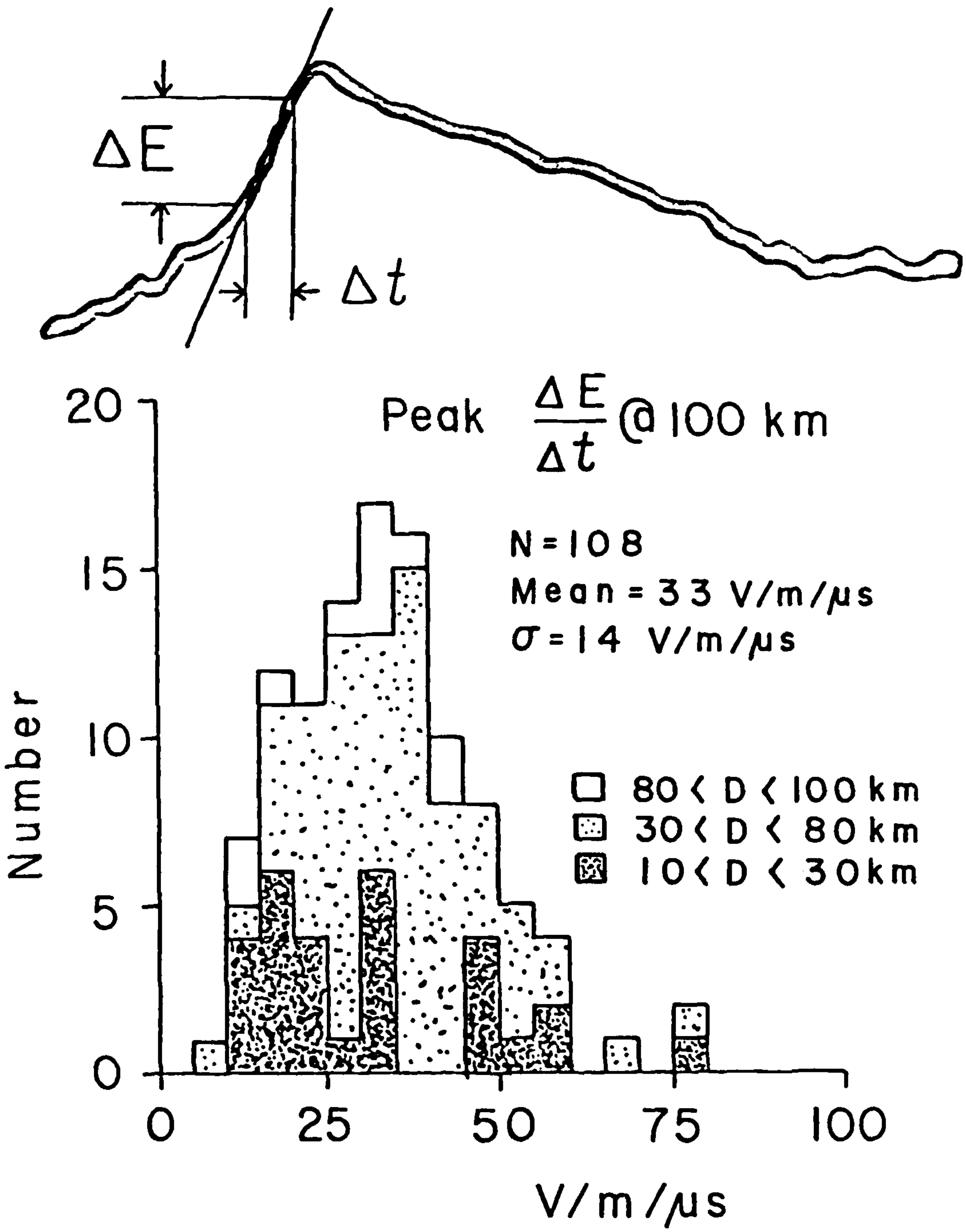

Figure 1. A Histogram of the Measured Maximum ΔE/Δt Values for Return Strokes Normalized to a Range of 100 km (from Weidman, 1982).

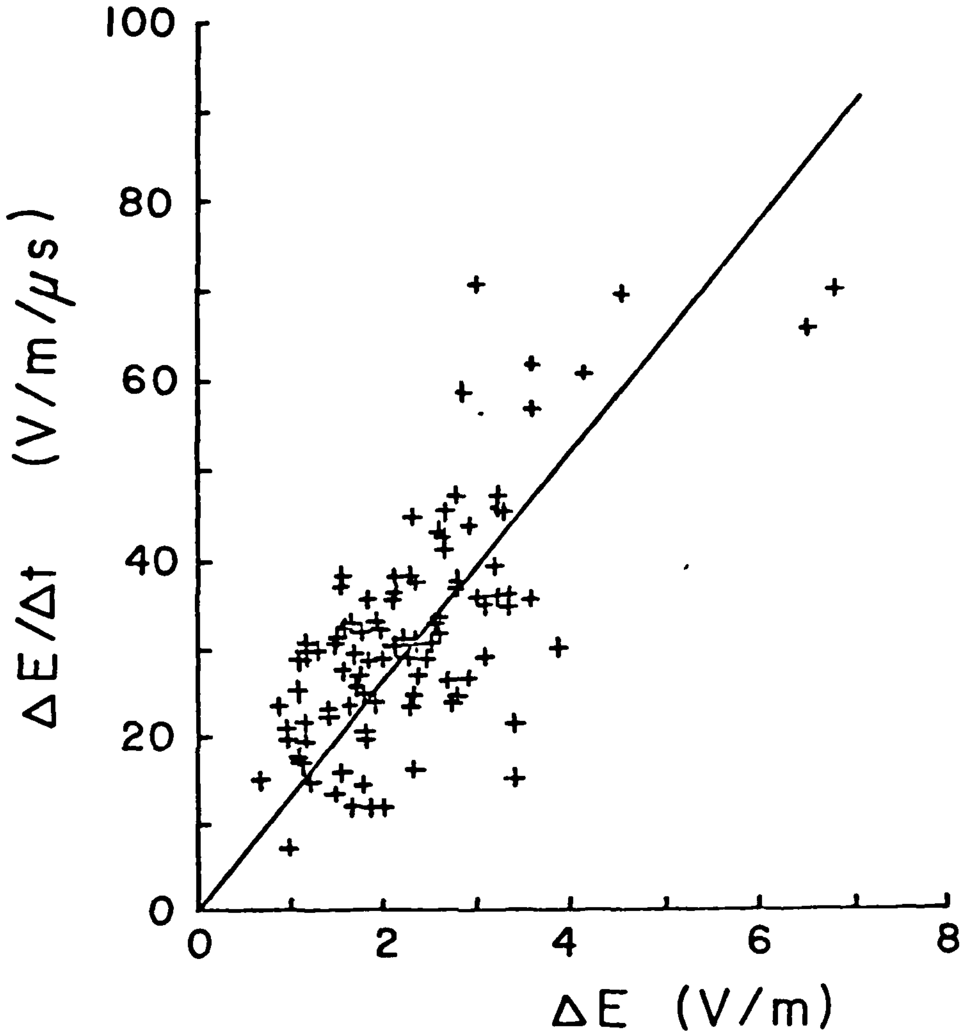

Figure 2. The Correlation Between Return Stroke ΔE/Δt and ΔE Range Normalized to 100 km (from Weidman, 1982).

this value, e.g. by two channels radiating simultaneously, but there is still no direct evidence that this suggestion is valid.

Fig. 3 summarizes all the available data on the values of the maximum return stroke $^{dI}/dt$. The data for the field-derived $^{dI}/dt$ are plotted assuming a return stroke velocity of 1×10^8 m/s. The dotted lines show where these data would fall if the velocity were either 1.4×10^8 or 0.6×10^8 m/s. It is clear from this figure that the average field-derived $^{dI}/dt$s correspond to the maximum values of the tower measurements for subsequent strokes and that the tower values for first strokes are significantly lower than those for subsequent strokes.

As noted earlier, the validity of our model relating fields and currents is supported by the French measurements on triggered lightning, and we think this model, which assumes that an upward propagating current pulse is associated with the return stroke wavefront, is the best that is currently available. An alternate model, which assumes that a spatially uniform but time-varying current propagates upward, the so-called Bruce-Golde model, yields a field-derived $^{dI}/dt$ that is within a factor of 2 of that found with our model. It has also been suggested (Uman et al., 1973; Weidman and Krider, 1978) that the initial first stroke field may be produced by currents propagating both upward and downward from the junction between the upward and downward leaders. This effect would lower our field-derived $^{dI}/dt$ by a factor of 2; but such an effect should not occur in subsequent strokes and these are observed to have about the same $^{dE}/dt$ and hence $^{dI}/dt$ as first strokes.

Once the lightning currents are known, the fields can easily be calculated from Maxwell's equations. Essentially all of the high frequency content of the field is determined by the current rise to peak and the current fall just after the peak, so the validity of the current model after the peak is of secondary

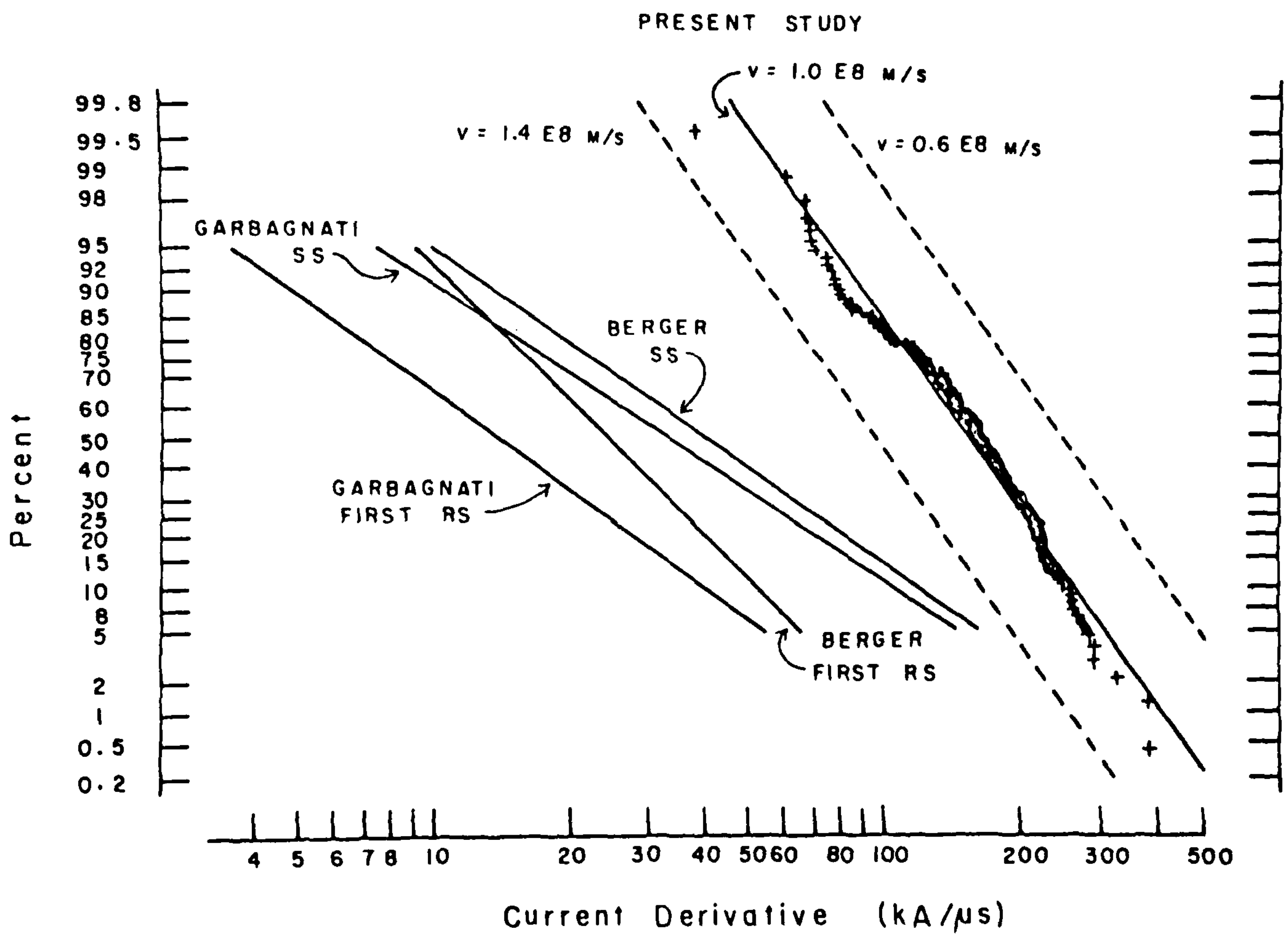

Figure 3. The Distribution of the Maximum $^{dI}/dt$ in Return Strokes Derived from Field Measurements (from Weidman, 1982).

importance in the lightning-NEMP comparison. This comparison is given in Figs. 1, 2, and 3 in the Appendix. Appendix Figs. 1 and 2 give magnetic fields computed at 1 m from the channel for average and severe first and subsequent strokes Appendix Fig. 3 gives electric fields at 50 m for a severe first return stroke. The NEMP spectra are shown in each of these three figures. Note that the average and severe return stroke spectra all have the same shape but differ in magnitude by 14 db, a factor of 5. Conclusions to be drawn from these figures are discussed in detail in the Appendix.

As an extension of these calculations, Fig. 4 shows electric field spectra for an average first stroke at distances between 50 m and 10 km. The dashed lines in Fig. 4 show the spectra of just the radiation field term so the contribution of the electrostatic and induction fields can be evaluated. At 10^7 Hz, the spectral amplitude at each distance is almost entirely due to the radiation field term.

An aircraft in flight probably will not encounter the return strokes considered above; but, on the other hand, the maximum $^{dE}/dt$ values in cloud pulses and leader steps and the associated amplitude spectra above 10^6 Hz are very similar to those of return strokes (Weidman et al., 1981). Although we do not yet have a model for these processes in which we are confident, the available measurements imply that the maximum current derivatives in these processes are comparable to return strokes. Therefore, we expect that the hazards from the high frequency components of cloud discharges may well be similar to return strokes near the ground.

Tortuosity

Levine and Meneghini (1978a) have used a simple current model to calculate the fields which are radiated by a tortuous channel and have shown that the

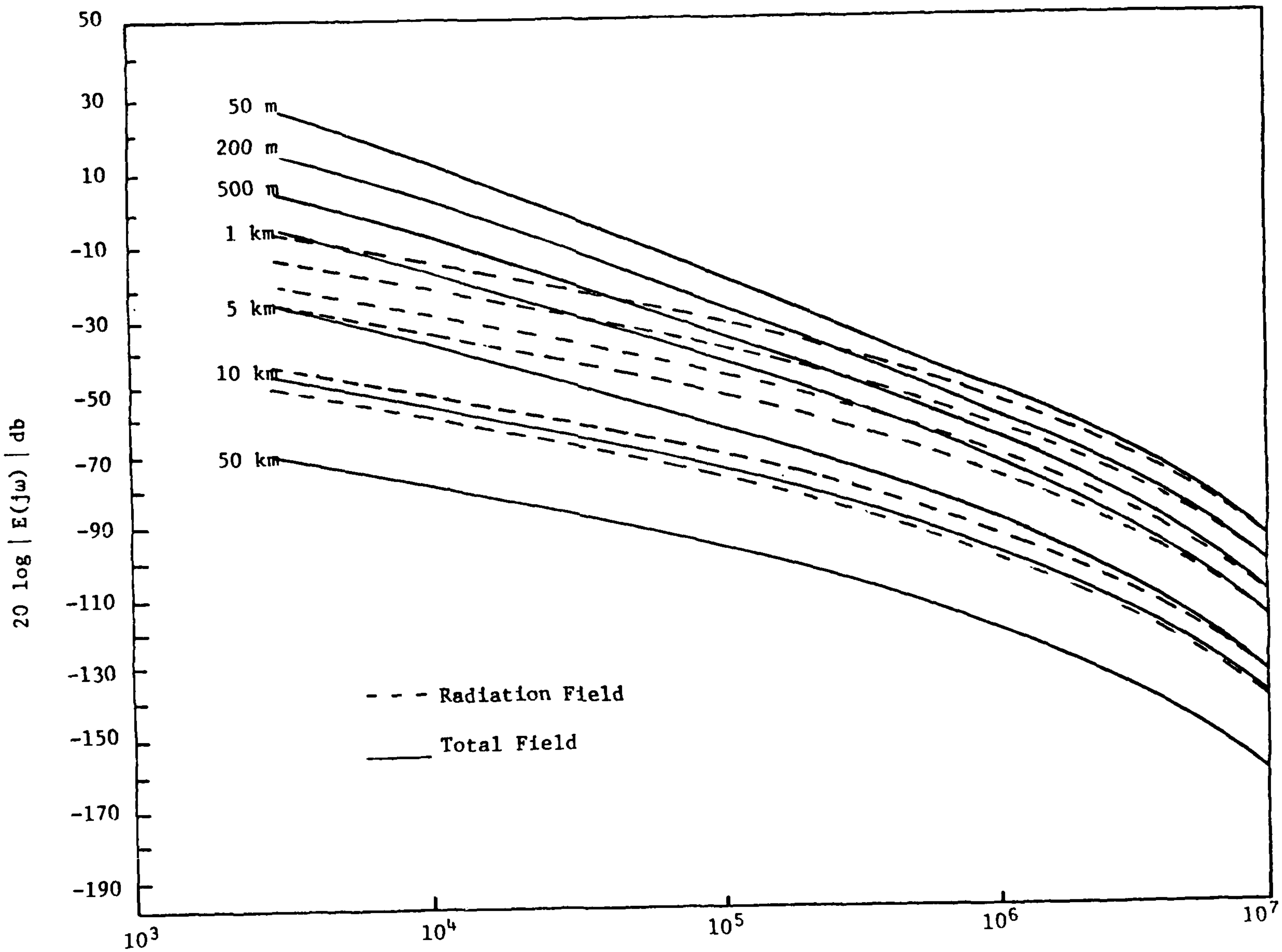

Figure 4. Electric Field Amplitude Spectra for an Average First Stroke vs. Range. The Spectra of just the Radiation Field are Shown as Dashed Curves.

tortuosity increases the "jaggedness" of a time-domain waveform and increases the spectral amplitude above 10^5 Hz by about 20 db. We have repeated their calculations for both distant and close (50 m) fields for a first stroke that has the current parameters given in Appendix Table 1a. The channel tortuosity is that given in Fig. 2 of Levine and Meneghini (1978b). The results are shown in Fig. 5, and it is clear that tortuosity does not appreciably alter the spectrum of the electrostatic or induction components which dominate the fields at close ranges. The change in the radiation field spectrum with tortuosity is an increase of about 10 db above 10^5 Hz. These calculations are critically dependent on the channel current waveform and the assumed tortuosity. On the other hand, the time-domain waveforms for the simulated tortuosity are much more "jagged" than the experimental data, which for subsequent strokes are actually quite smooth, so the effects of tortuosity may not be nearly as large as these calculations would indicate. In fact, most of the frequency content above 10^6 Hz in the measured time-domain fields from first and subsequent strokes is produced within 1 μsec or so of the peak field; and this implies that most high frequencies are radiated at a time when the stroke is within a few hundred meters of ground and prior to the time when tortuosity can play a significant role. Why subsequent stroke field waveforms are smooth when photographed channels appear to have considerable tortuosity is not clear. Currently, there are studies under way at the University of Arizona to measure tortuosity and branching in real channels, and in the future these will be coupled with calculations of fields by the University of Florida. We hope that these future studies will resolve this apparent contradiction.

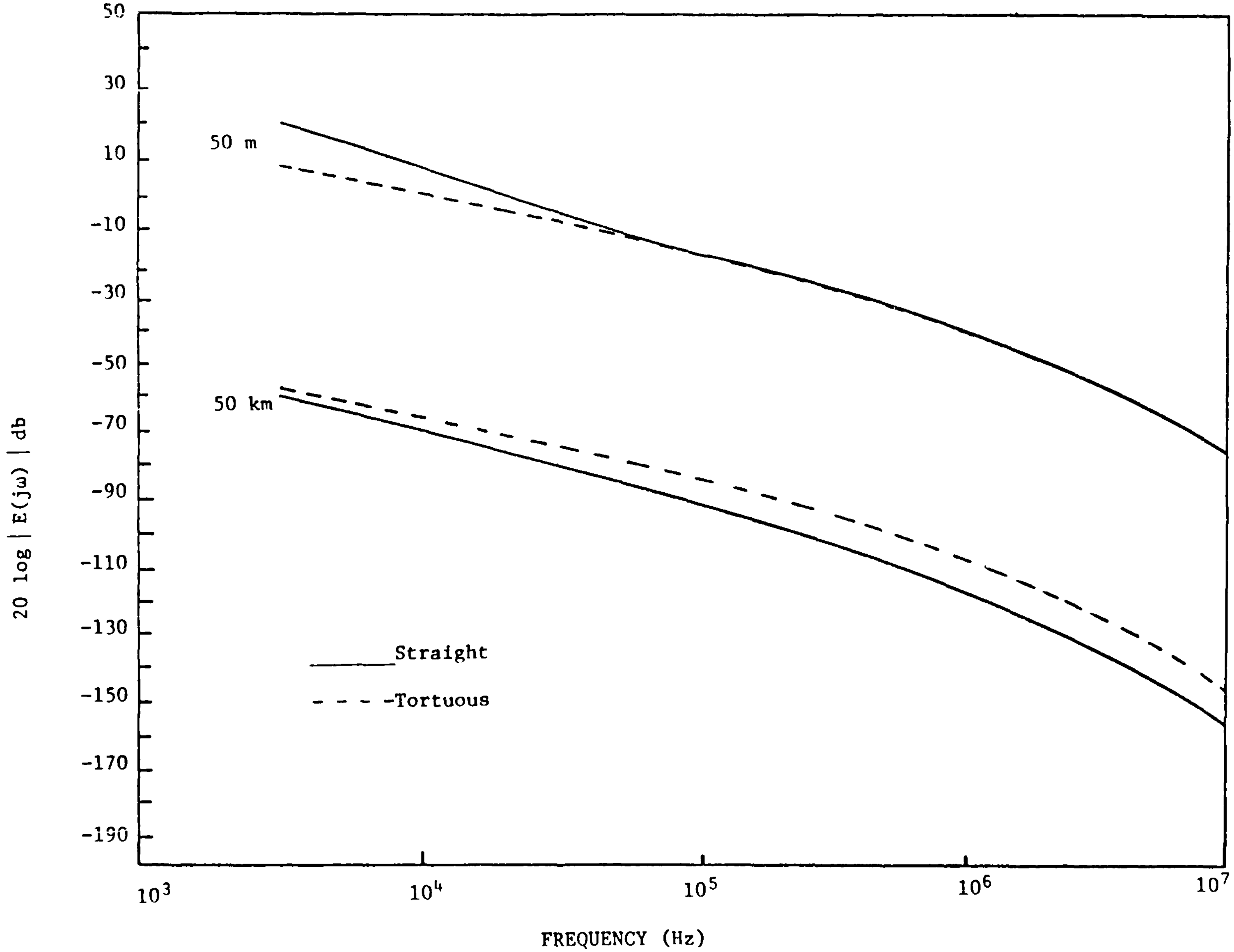

Figure 5. Electric Field Amplitude Spectra for Straight and Tortuous First Return Strokes at 50 m and 50 km

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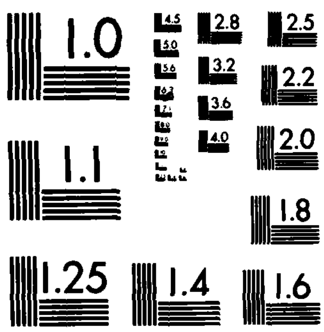

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

APPENDIX

A Comparison of Lightning Electromagnetic Fields with the Nuclear Electromagnetic Pulse in the Frequency Range 10^4 to 10^7 Hz

(Since this document was published in the IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-24, No. 4, pp 410-416, November 1982, only the abstract is reproduced here.)

A Comparison of Lightning Electromagnetic Fields with the Nuclear Electromagnetic Pulse in the Frequency Range 10^4 to 10^7 Hz

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ABSTRACT

The electromagnetic fields produced by both direct lightning strikes and nearby lightning are compared with the nuclear electromagnetic pulse (NEMP) from an exoatmospheric burst. Model calculations indicate that, in the frequency range 10^4 to near 10^7 Hz, the Fourier amplitude spectra of the return stroke magnetic fields near ground 1 m from an average lightning strike will exceed that of the NEMP. Nearby first return strokes at a range of about 50 m, if they are severe, produce electric field spectra near ground which exceed that of the NEMP below about 10^6 Hz, while the spectra of average nearby first return strokes exceed that of the NEMP below about 3×10^5 Hz. Implications of these results for aircraft in flight are discussed.

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Appendix B

INTERPRETATION OF SPECTRA OF COMPLEX ELECTROMAGNETIC EVENTS

1. INTRODUCTION AND BACKGROUND.

As indicated in Section II-C, spectral information historically has been used in describing lightning characteristics. In general, the earlier measurements were made using a multiplicity of receivers sampling the frequency range of interest. A measurement of this sort yields information only about the spectral amplitude function. Some of the characteristics of such spectral measurements will be discussed here.

As discussed in Section II-A, a single lightning event -- either a cloud-to-ground flash or an intracloud flash -- contains thousands of individual pulses having a variety of amplitudes, rise times, durations, and pulse separations. These pulses are associated with the currents flowing in the lightning channel and with the fields radiated by these stroke currents and by precursor discharges within the cloud. When an aircraft in flight is excited by a lightning flash (either by direct attachment of a stroke to the aircraft or by interaction with the fields of a nearby stroke), electrical transients are induced on the internal equipment wiring.

The nature of these internal transients depends on the following:

- Spatial distribution of the source fields with respect to the aircraft.
- Source waveshape or spectrum (including amplitude and phase).
- Transfer functions describing the coupling between the external source and the internal wiring (amplitude and phase).

Therefore, any analysis or discussion of the effects of lightning on a particular electronic subsystem within an aircraft must consider the source spectrum (amplitude and phase) and the coupling transfer function (amplitude and phase) appropriate for the equipment terminals of interest. For linear sytems, the spectrum of the voltage appearing at equipment terminals can be written

$$V(\omega) = S(\omega)T_V(\omega) \quad , \tag{B-1}$$

where V, S, T_V are the induced voltage spectrum, the source spectrum, and the coupling transfer function, respectively.

The following paragraphs discuss these elements of the problem. The objective of the discussion is to focus on the differences between the spectrum of an individual pulse within the pulse train and the spectrum of the complete pulse train. This will lead to a better understanding of the important differences between lightning spectra observed with wideband and narrowband measurement systems.

2. THE SOURCE SPECTRUM.

The source can be considered the current in the lightning flash (for direct attachment) or the fields radiated by the flash. The flash can be represented as the sum of many discrete pulses, or

$$S(t) = \sum_{i=1}^{N} s_i\,(t - T_i) \quad , \tag{B-2}$$

where N is the number of discrete pulses in the flash, s_i is the i^{th} pulse in the train of pulses, and T_i is the time at which the i^{th} pulse begins. It is convenient to model individual pulses s_i as the difference of two exponentials, or

$$s_i(t - T_i) = A_i U(t - T_i) \left\{ \exp\left[-a(t_i - T_i)\right] - \exp\left[-b\,(t_i - T_i)\right] \right\} \quad , \tag{B-3}$$

where A_i is a constant related to the peak amplitude of the i^{th} pulse, $U(t - T_i)$ is the step function, and a_i and b_i are parameters determining the rise time and fall time of the i^{th} pulse.

An expression for the transform $S(\omega)$ of Eq. B-2 can be obtained by standard methods with the following assumptions:

- Each pulse dies away before the next one begins.
- The pulses are aperiodic, and T_i is a random variable.

These assumptions lead to the following expression for the source amplitude spectrum $|S(\omega)|$:

$$|S(\omega)| = \left\{ \sum_{i=1}^{N} \frac{N\ A_i^2\,(a_i - b_i)^2}{(a_i^2 + \omega^2)(b_i^2 + \omega^2)} \right\}^{1/2} \quad . \tag{B-4}$$

If all the individual pulses are identical, Eq. B-4 can be expressed as

$$|S(\omega)| = \frac{A(a-b)\sqrt{N}}{\sqrt{(a^2 + \omega^2)(b^2 + \omega^2)}} \quad . \tag{B-5}$$

The response characteristics of a narrowband system excited by a pulse train can be seen from the following example. Let us assume that the lightning stroke current is composed of double-exponential components of two types: wide pulses corresponding to "return strokes," and narrow pulses corresponding to "leader strokes." All pulses in the train are assumed to be of the double exponential type shown in Eq. B-3.

The wide pulses are assumed to have exponential constants $a = 2 \times 10^4\ s^{-1}$ and $b = 10^6\ s^{-1}$. This corresponds to a return stroke having a rise time of about 1 μs and a pulsewidth of about 50 μs. The amplitude was chosen to produce unity $S(\omega)$ at low frequencies.

The narrow pulses are assumed to have peak amplitudes 1/100 of the wide-pulse amplitude and to have exponential constants $a = 5 \times 10^6\ s^{-1}$ and $b = 9.7 \times 10^7\ s^{-1}$. Thus, the narrow pulse corresponds to a leader stroke with a peak amplitude of 1/100 that of the "return stroke" and with a rise time of about 30 ns and a pulsewidth of about 200 ns.

Figure B-1 shows the spectra of the individual pulses being considered. At low frequencies, the wide pulse has more spectral energy than the narrow pulse. For frequencies above 10 MHz, both pulses have comparable spectral amplitudes.

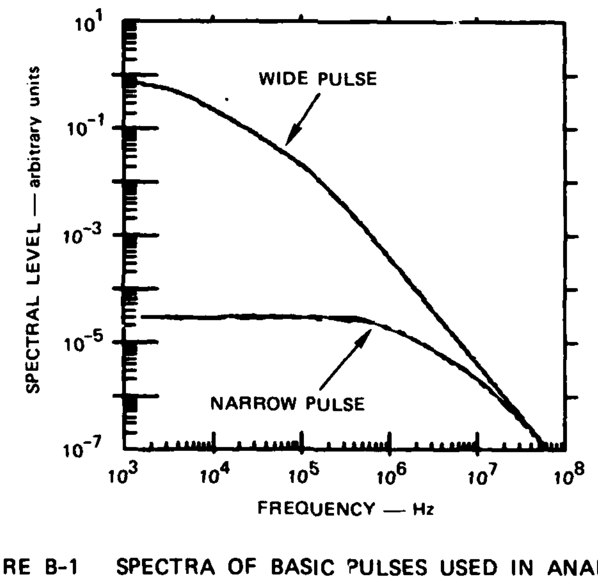


FIGURE B-1 SPECTRA OF BASIC PULSES USED IN ANALYSIS

Now assume that the pulse train contains one wide pulse and 100 narrow pulses. Application of Eqs. B-4 and B-5 results in the composite spectrum shown in Figure B-2. The low-frequency (below 500 kHz) amplitude of the composite spectrum is relatively unaffected by the presence of the narrow pulses, but the high-frequency part of the spectrum is altered considerably by the presence of the narrow pulses.

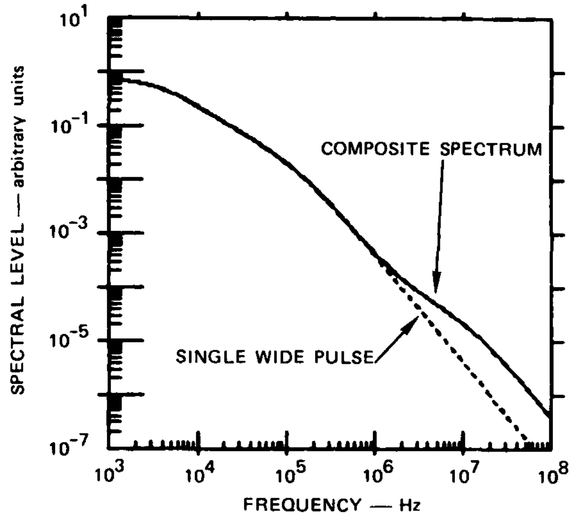


FIGURE B-2 SPECTRUM OF SINGLE WIDE PULSE AND 100 NARROW PULSES

If the pulse train is now assumed to contain one wide pulse and 1000 narrow pulses, the spectrum of Figure B-3 is obtained. Here the added narrow pulses have extended the composite spectrum to substantially higher frequencies.

Figures B-1 through B-3 indicate the nature of the composite spectrum of a pulse train simulating a lightning flash. The following points are emphasized:

- The low-frequency part of the composite spectrum is dominated by the widest pulses in the pulse train.
- The high-frequency part of the composite spectrum is significantly influenced by the presence of the many narrow pulses.

These points are important in considering the application of the results of narrowband lightning spectral measurements to aircraft lightning problems. This topic is discussed in greater detail below.

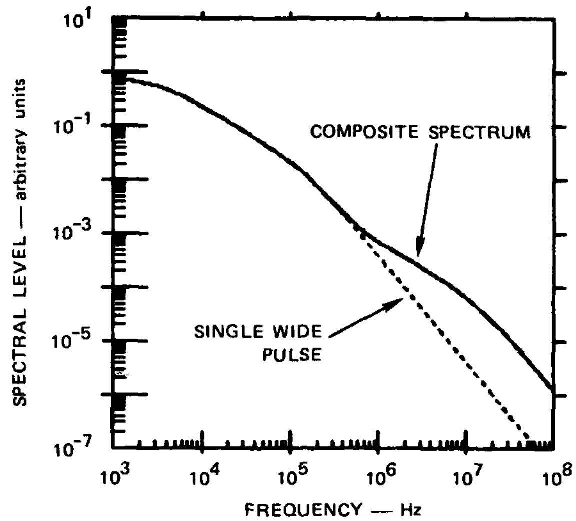


FIGURE B-3 SPECTRUM OF SINGLE WIDE PULSE AND 1000 NARROW PULSES

3. TYPICAL INTERNAL RESPONSES FOR AIRCRAFT.

As indicated in Section IV-A3, measurements of the currents induced on internal aircraft wiring by wideband external field pulses have indicated that the response typically exhibits a damped oscillatory nature. The major internal ringing frequencies for most aircraft are in the range above 1 MHz (usually in the range of 10 to 100 MHz), and the durations of the internal responses are typically less than a few microseconds. The response to a train of pulses depends on the time interval between pulses in the source pulse train. If the typical source pulse separation is greater than a few microseconds, then the responses to each individual source pulse decay to zero before the next pulse arrives. If the source pulse separation is less than a few microseconds, then the responses to each source pulse overlap in time.

Review of published lightning data indicates that pulse separations of tens of microseconds or more are appropriate for the stepped leader phase of the flash, and that separations of many milliseconds are typical in the late stages of an intracloud flash.[77] Since most internal transients decay to zero in only a few microseconds, the typical response to excitation by a train of lightning pulses is a train of damped oscillations with little or no overlap. Thus, the time waveforms of the individual processes in the lightning flash should be considered -- not the composite spectrum.

It is important to emphasize here that, strictly speaking, a determination of the internal current and voltage transients induced by a train of lightning pulses requires the rigorous application of Eq. B-1. That is, both the amplitude and phase of the source spectrum are instrumental in determining the response inside an aircraft. So-called lightning "spectra" derived from narrowband measurements cannot be applied to this problem. These "spectra" are obtained after filtering, detecting, and integrating the pulse train, and since phase information is completely lacking, they are not directly applicable to determining transient responses inside an aircraft.

Appendix C

AIRCRAFT LIGHTNING-RELATED ACCIDENT EXPERIENCE

Summaries of aircraft lightning experience and the resulting effects on aircraft systems are discussed in References 67 through 75. Reference 67 presents a thorough review of data available up to 1980 for both commercial and military aircraft.

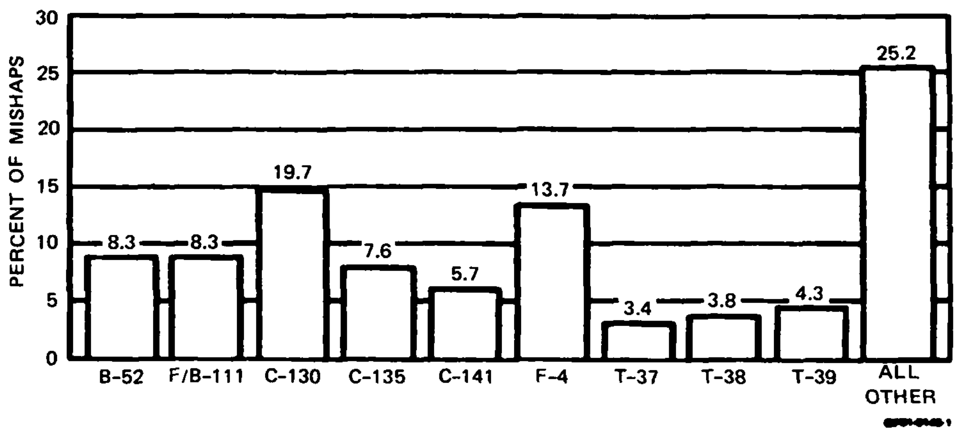
1. MILITARY AIRCRAFT EXPERIENCE.

The extent of the problem for the USAF is succinctly summarized in the following, which is extracted verbatim from Reference 68 and which represents USAF statistics as of February 1979:

> "More than half of all Air Force weather-related aircraft mishaps are caused by lightning strikes. The USAF financial loss incurred in such mishaps exceeds 21 million dollars in the past five years, besides two aircraft lost with eight lives in 1978 alone. In the past ten years, seven USAF aircraft losses have been confirmed as lightning-related, two others ascribed to lightning as a likely cause, and over 150 serious mishaps reported. Imputed mechanisms include pilot disorientation and instrument failure (F-101, F-106), flight control failure after high current penetration (F-111F), fuel tank explosion, dual engine flameouts with electrical failure (F-4), fuel tank burnthrough and explosion (C-130E), and failure of unprotected nonmetallic rotor blades (HH-33). A probable lightning-associated fuel ignition caused the loss of an Imperial Iranian Air Force 747 aircraft on 9 May 1976 near Madrid, Spain."

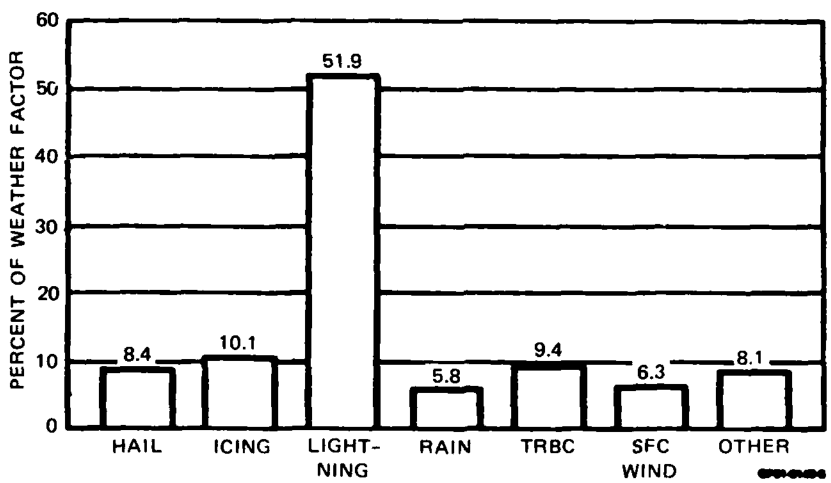
The percent of USAF aircraft mishaps by type is shown in Figure C-1; the effects of various atmospheric phenomena are shown in Figure C-2, where over half of all mishaps are shown to be caused by lightning. Some lightning-strike data for the F-4 aircraft are seen in Figures C-3 and C-4, which show the effects of both altitude and global location. These figures indicate that specific missions and theaters of operation are very significant factors in determining the probability of a strike to an aircraft.

Tables C-1 and C-2 contain additional data on the severity of lightning interactions with military aircraft.



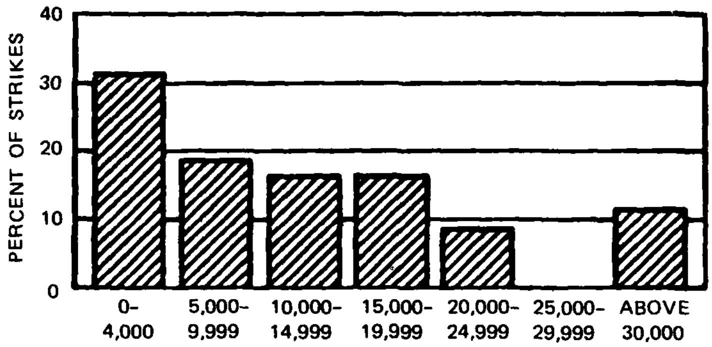
SOURCE: Reference 69

FIGURE C-1 PERCENT OF MISHAPS BY AIRCRAFT TYPE (1973-1977)



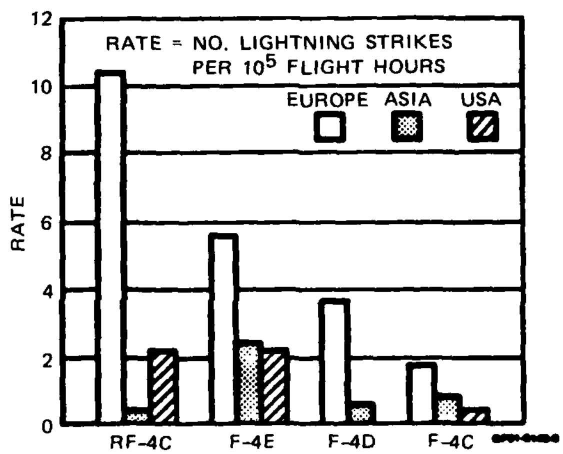
SOURCE: Reference 69

FIGURE C-2 MISHAP CAUSES (1972-1977)



SOURCE: Reference 70

FIGURE C-3 LIGHTNING STRIKES TO F-4 AIRCRAFT AS A FUNCTION OF ALTITUDE



SOURCE: Reference 70

FIGURE C-4 RATES OF LIGHTNING STRIKES TO F-4 AIRCRAFT

Table C-1

TEN YEAR HISTORY OF USAF LIGHTNING INCIDENTS

A/C	STRUCTURE	ELECTRICAL, INSTRUMENTS	FUEL	OTHERS	CATASTROPHIC	MAJOR	MINOR
F101	1	4		1	1	2	3
F102				3			3
F106	3	5			1	2	5
F-111*	3	15		6	1*	1	22
F-4	14	26	4	6	2	1	47
F-15	1	1					2
T-29	3	2		1			6
T-38	2	1					3
C119		1			1		
C124	1						1
C130**	4	6	1**	1	1**		11
C131	3	2					5
KC135	8	5	1		1		13
C141	3	3					6
OTHER	7	5					12
B-52	12	2		1		1	14
HH-43	1				1		
TOTALS	66	78	6	19	9	7	153

*F-111F lost 29 March 78 near RAF Lakenheath, UK with two crew fatalities. Lightning effects on electrical and electronic control subsystems were a factor.

**C-130E lost 30 Nov 78 near Charleston, SC with 6 fatalities. Lightning burn-through of wing skin by attached stroke caused fuel tank explosion.

Table C-2

LIGHTNING AND STATIC ELECTRICITY THREATS TO AIRCRAFT (FROM REF 71)

Hazard	Cause	Hazard Criticality
Malfunction/Failure of Electronic Control Systems	Low Tolerance to Electrical Transients Caused by Direct/Induced Lightning or Static Electrification Effects, May Simultaneously Affect Parallel "Redundant" System	Minor to Catastrophic
Fuel Tank Fire or Explosion	Fuel Vapor Ignition Caused by Static Electricity of Lightning Effects	Minor to Catastrophic
Loss of Engine Power	Possible Lightning Acoustic Shock at Engine Inlet, or Electrical Transient Effects on Engine Controls	Minor to Catastrophic
Inadvertent Release/Ignition of External Stores	Premature Activation Caused by Lightning or Static Electrification Effects	Serious to Catastrophic
Radome, Canopy, and Windshield Damage	Direct Lightning Strikes; Arc Discharge Caused by Static Electricity Buildup	Minor to Serious
Instrumentation Problems/ Communications, Navigation and Landing System Interference	Transient Effects Caused by Static Electricity Buildup and Direct and Nearby Lightning Strikes	Minor to Catastrophic
Structural Damage	Direct Lightning Attachment to Aircraft	Minor to Serious
Physiological Effects on Crew	Flash Blindness and Distracting or Disabling Electrical Shock Caused by Direct and Nearby Lightning Strikes	Minor to Catastrophic

Recently, Corbin reviewed Air Force lightning mishap reports covering the period 1970-1982.[72] The total number of reports arranged by aircraft class is shown in Table C-3. The percentage distribution is very similar to that obtained when the data of Figure C-1 are combined according to aircraft class.

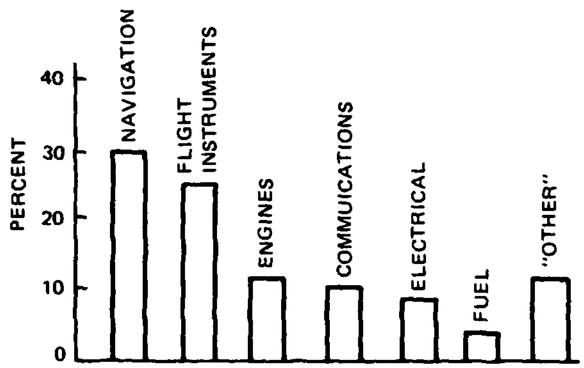
Table C-3

USAF LIGHTNING MISHAP REPORTS BY
AIRCRAFT CLASS (1970-1982) (REF 72 CORBIN)

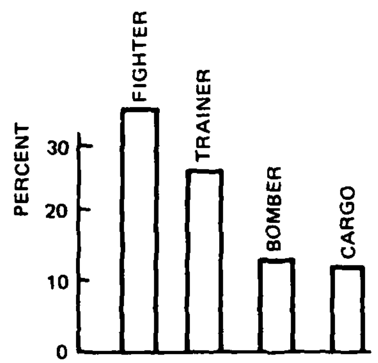
Aircraft Class	Mishap Reports
Attack	13
Bomber	83
Cargo	434***
Fighter	282****
Trainer	75
Helicopter	5
TOTAL	892

Asterisk denotes loss of one aircraft

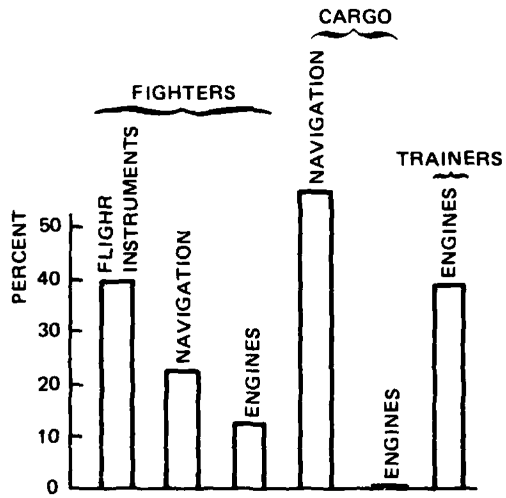
Data from Reference 72 on the interference/outages attributed to lightning strikes are shown in Figure C-5. A breakdown showing the systems affected is shown in Figure C-5a. Navigation systems and flight instrumentation are the most vulnerable overall. Figure C-5b indicates that small aircraft typified by fighters and trainers are more vulnerable to lightning than larger aircraft such as bombers and cargo aircraft.



(a) SYSTEM AFFECTED BY STRIKE -- ALL AIRCRAFT



(b) FREQUENCY OF OCCURRENCE OF EFFECTS FOLLOWING STRIKE FOR VARIOUS AIRCRAFT TYPES



(c) SENSITIVITY OF AFFECTED SYSTEM TO AIRCRAFT TYPE

DEFINITION OF TERMS

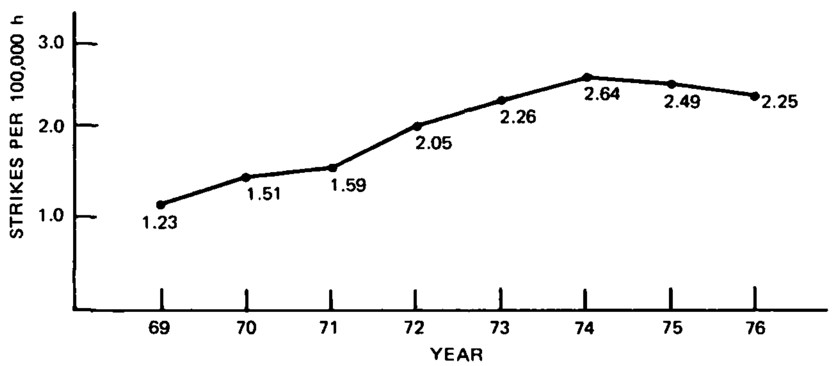
Communication	Navigation	Flight Instruments	Engine	Electrical	Fuel	Other
VLF	OMEGA	Indicators (altimeter, angle of attack, airspeed)	Flameout	Generator	Explosion/Fire	EW Jammers
HF	LORAN	CADC	Rollback	Circuit Breaker	Flow/Quantity Gauge	Radar Warning
VHF	ADF	Autopilot	Compressor Surge	Fuse	Venting	IFF
UHF	VOR		Compressor Stall	Warning/Caution Light		Environmental Controls/ Instruments
Transmitters/ Receivers	ILS		RPM Gauge	EED		
	TACAN		Engine Warning Light	Transformer		
	DME			Aircraft Power		
	Weather Radar			Pitot/Windshield Heater		
	Nav. Computer Compass			Internal Lights		

SOURCE: Reference 72

FIGURE C-5 INTERFERENCE/OUTAGE FOLLOWING A LIGHTNING STRIKE (from 183 Report -- 239 events)

Figure C-5c indicates that the system affected most strongly depends upon the aircraft type. Flight instrumentation and navigation were most affected in fighters, while navigation was predominantly affected in cargo aircraft. These differences can in part be explained in terms of lightning attachments to the pitot system and air data sensors on fighter aircraft (which impacts flight instrumentation indicators), and a high percentage of attachments to the nose radome on cargo aircraft (which impacts weather/navigation radar). Engines were affected in fighters and trainers, but were not a factor in cargo aircraft.

Figure C-6 indicates recent lightning strike rate experience.[71] It is likely that the increasing strike rate reflects increasing operation under instrument conditions.



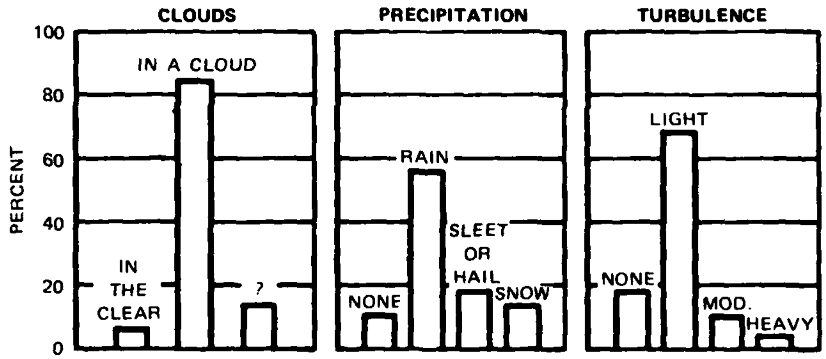
SOURCE: Reference 71

FIGURE C-6 THREE-YEAR RUNNING AVERAGE OF USAF LIGHTNING STRIKE RATES (1969-1976)

2. COMMERCIAL AIRCRAFT EXPERIENCE.

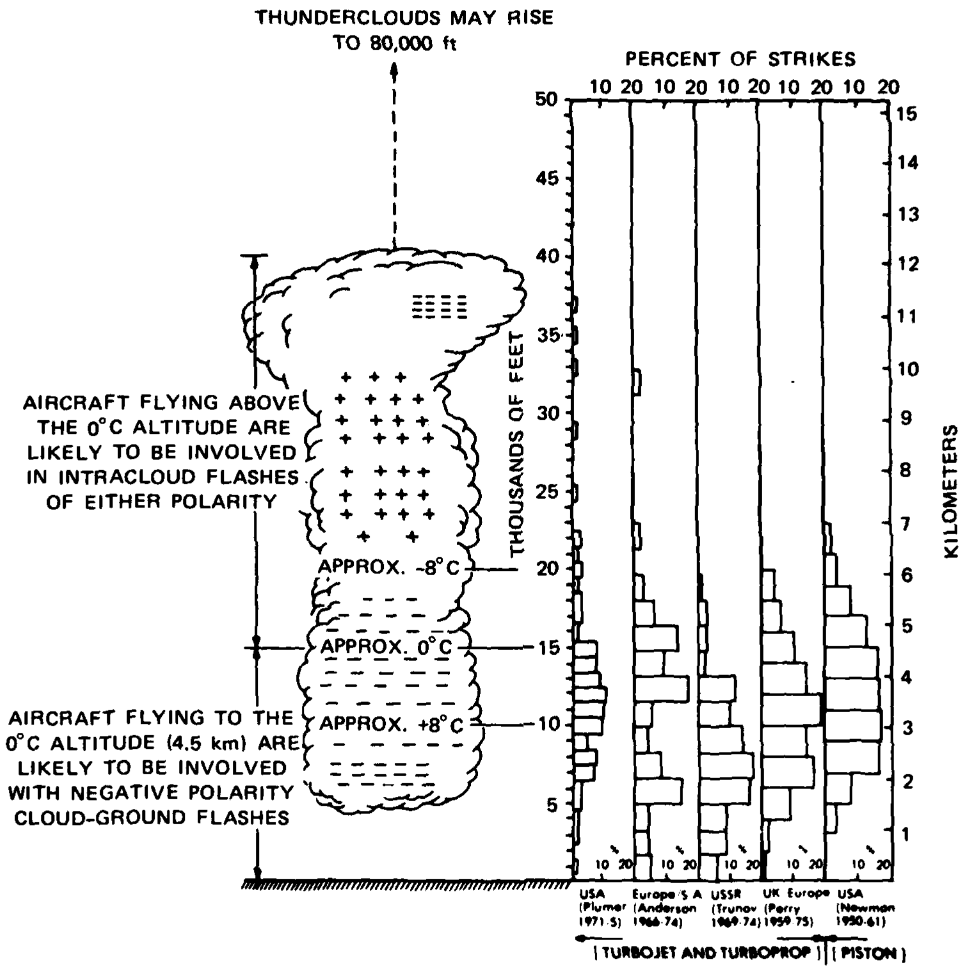
Excellent summaries of commercial aircraft experience with lightning may be found in References 73 through 75. Commercial aircraft encounter direct strikes at the rate of about once per 3,000 hours of operation, while military craft are struck once per 20,000 hours. This difference indicates the effect of mission and location on the strike frequency. Both numbers are expected to decrease (the frequency of incidents will rise) in the future, as commerical aircraft will be making more stops on their routes and will be held in the air for longer periods in traffic control patterns. Military aircraft will be expected to fly in more severe weather than they have been exposed to in the past.

Figures C-7 and C-8 describe the statistics concerning commercial aircraft experience as a function of altitude and environmental conditions. Tables C-4 and C-5 describe the incidence of strikes to commercial aircraft and the effects observed in these aircraft.



SOURCE: Reference 73

FIGURE C-7 ENVIRONMENTAL CONDITIONS AT TIME OF STRIKE



SOURCE: Reference 73

FIGURE C-8 AIRCRAFT LIGHTNING-STRIKE INCIDENTS vs ALTITUDE

Table C-4

INCIDENCE OF LIGHTNING STRIKES RELATIVE TO AIRCRAFT TYPE, ZONE OF OPERATION, AND FLYING HOURS (UK DATA ONLY)

Type of Aircraft	Zone of Operation	Period Covered	No. of Strikes	Total Flying Hours	Incidence of Strikes
Viscount	Europe	March 1959 to June 1964	195	567,000	1/2900 hrs
Vanguard	Europe	May 1961 to June 1966	79	194,000	1/2500 hrs
Comet 4B	Europe	June 1960 to June 1966	86	162,000	1/1900 hrs
Trident	Europe	May 1964 to June 1968	92	140,000	1/1500 hrs
BAC 1-11	Europe	January 1969 to April 1970	72	56,000	1/780 hrs
Britannia	World-Wide	October 1959 to April 1961	6	115,000	1/19000 hrs
Boeing 707	World-Wide	January 1962 to December 1967	103	458,000	1/4400 hrs
VC.10	World-Wide	August 1964 to June 1970	75	361,000	1/4800 hrs
Boeing 747	World-Wide	June 1971 to December 1974	52	137,000	1/2600 hrs
Total	Europe	-	524	1,119,000	1/2100 hrs
Total	World-Wide	-	236	1,071,000	1/4500 hrs
Total	Europe and World-Wide	-	760	2,190,000	1/2900 hrs

Source: Reference 75

Table C-5

EVIDENCE OF INDIRECT EFFECTS IN COMMERCIAL AIRCRAFT (214 STRIKES IN PERIOD JUNE 1971 TO NOVEMBER 1974)

	Interference	Outage
HF communication set	–	5
VHF communication set	27	3
VOR receiver	5	2
Compass (all types)	22	9
Marker beacon	–	2
Weather radar	3	2
Instrument landing system	6	–
Automatic direction finder	6	7
Radar altimeter	6	–
Fuel flow gauge	2	–
Fuel quantity gauge	–	1
Engine rpm gauges	–	4
Engine exhaust gas temperature	–	2
Static air temperature gauge	1	–
Windshield heater	–	2
Flight director computer	1	–
Navigation light	–	1
ac generator tripoff	(6 instances of tripoff)	
Autopilot	1	–

Source: Reference 73

Appendix D

CURRENT AND PROJECTED AIRCRAFT WORK

As indicated in Section III-D, a number of aircraft measurement programs have been started in recent years. It is planned that all of these flight programs will be continued in various forms in the future.

1. NASA F-106.

Flight tests using the F-106 have been under way at NASA Langley since 1980. This test program is unique in that the objective of the program is to seek out and measure the properties of attached lightning strikes. The instrumentation system for this aircraft has been developed in an effort to meet the severe requirements on system bandwidth and data storage imposed by the electromagnetic properties of lightning. Sensors for the F-106 have been based on the designs evolved by C. Baum of AFWL for EMP studies. Special digital recording systems have been employed to maximize the length of record achievable per event. Until recently, only two recording channels were *available* in the system.

Starting in 1983, the F-106 was equipped with a 12-channel 100 MHz bandwidth recording system. This new system permits the simultaneous recording of several parameters and should provide greater insight into lightning properties and aircraft response. Further improvements to the recording system are planned.

Severe space limitations on the F-106 have precluded the use of a system to provide a slow-speed record of the lightning event as a whole. Thus, the experimenters are not certain of the nature of the lightning events responsible for the electromagnetic signals they observe. This difficulty is not expected to be surmounted in the immediate future.

In addition to gradually evolving their instrumentation, the F-106 experimenters are developing improved operating procedures to increase the likelihood of direct strikes to the aircraft. The first flight tests were conducted at altitudes of 16,000 ft and below with no provision to vector the aircraft to active regions of the cell. In 1982, the aircraft was flown over Wallops Island where a UHF radar is used to detect and locate lightning event channels. The radar system was used to vector the aircraft to active regions in the cloud. These turned out to be at an altitude of 20,000 to 25,000 ft. Thus, most of the data at this altitude were probably generated by intracloud processes.

The F-106 will be flown to AFWL for free-field testing using the vertically polarized dipole (VPD) system to further verify the working of the aircraft sensors and to investigate the effects of aircraft resonances. At present, it is planned that both stationary tests and flybys will be carried out. The tests are scheduled to begin in January 1984.

2. U.S. AIR FORCE AFFDL WC-130.

The WC-130 flight test program was terminated after the 1981 test period, since the aircraft was no longer available. Plans are currently being formulated to resume testing using a different aircraft. At present, it appears that a test program as early as summer 1984 may be possible.

During the tests using the WC-130 aircraft, every effort was made to avoid direct strikes to the aircraft. Beginning in 1984, it is planned that the new aircraft will be operated in such a way as to deliberately seek direct strikes.

It appears that the cooperative effort between the Air Force and ONERA (France) will continue, and that an instrumentation package developed by ONERA will be available for the projected flight tests. The objectives of the Air Force AFFDL tests will be similar to those of NASA. The different instrumentation packages carried on the two aircraft and the substantial differences in aircraft size will allow the two experiments to compliment one another in several important areas.

3. OFFICE NATIONALE D'ETUDES ET DE RECHERCHES AEROSPATIALES (ONERA) TRANSALL.

The ONERA instrumentation discussed in Section III-D has been carried on a few shakedown tests over France, using a Transall aircraft, but has not been used in a concerted test program. It is anticipated that the test aircraft will be available in 1984 for a period of systematic flight testing.

The sensors and recording instrumentation in the ONERA package are well thought out and have been thoroughly tested in the laboratory. Thus, their system will provide the opportunity for further comparison of flight test data on lightning parameters and aircraft responses.

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